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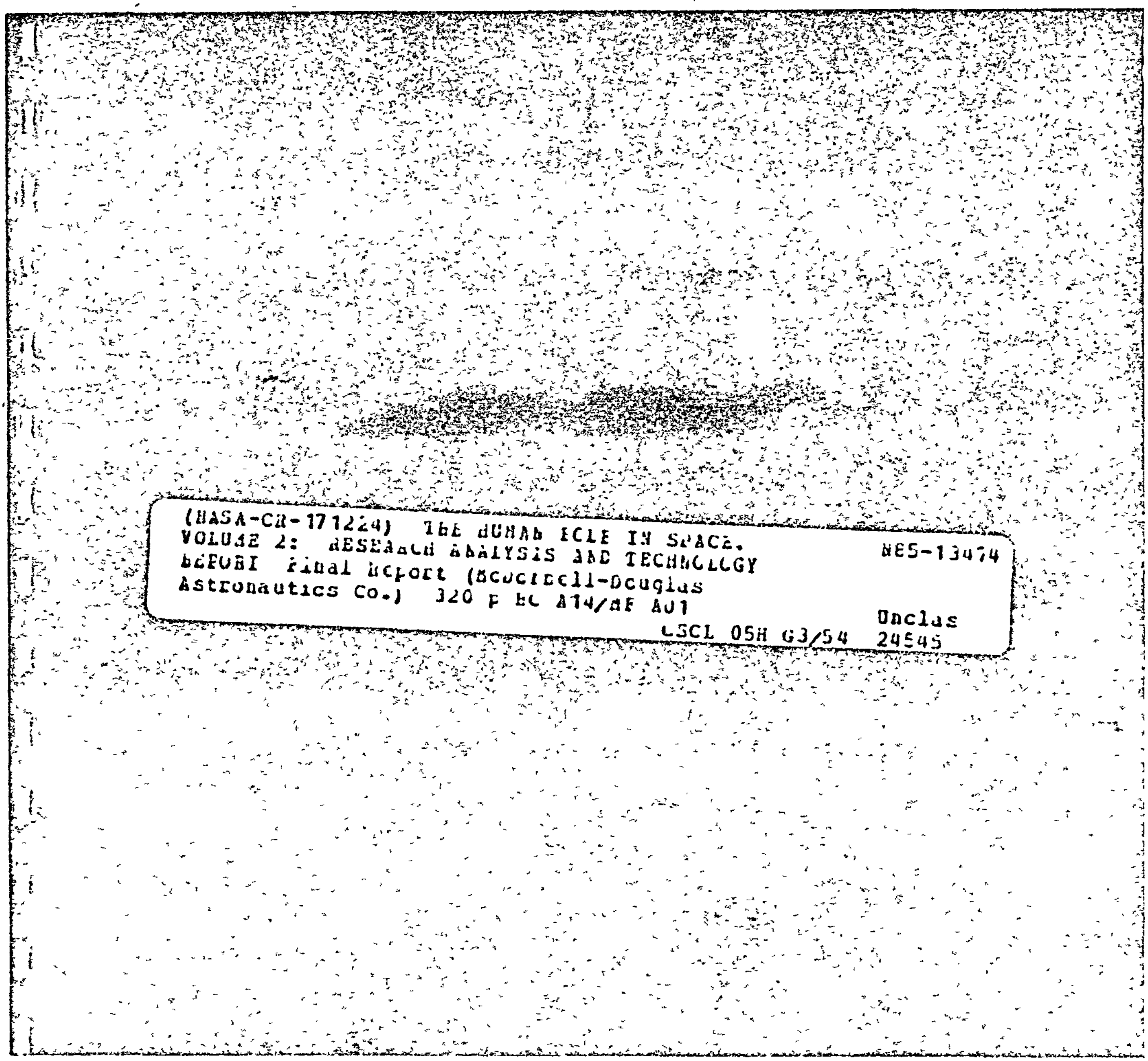

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THE HUMAN ROLE IN SPACE

Volume II – Reseach Analysis and Technology Report

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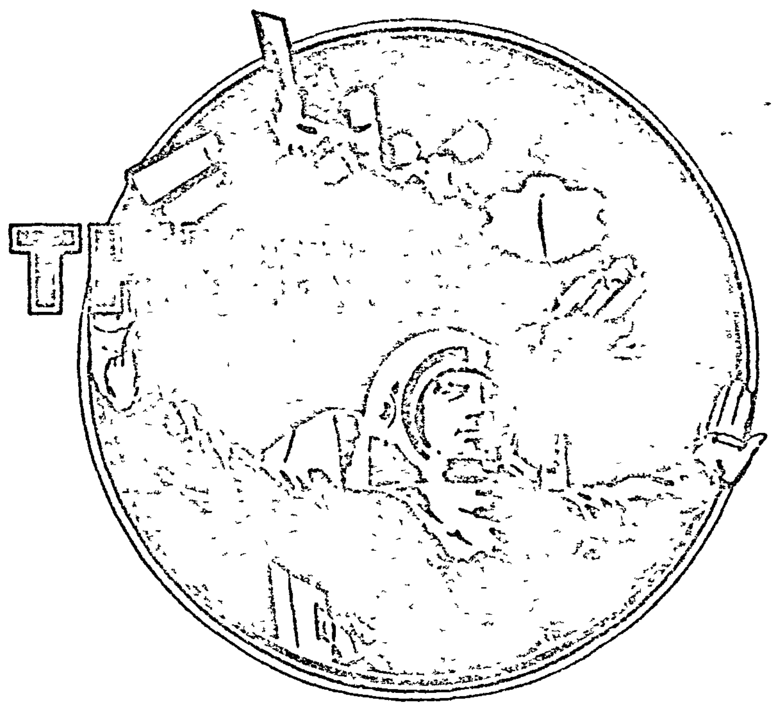

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY-HUNTINGTON BEACH
5301 Bolsa Avenue Huntington Beach California 92647 (714) 896 3311

PREFACE

The Human Role in Space (THURIS) study was a 12-month effort to (1) investigate the role and the degree of direct involvement of humans that will be required in future space missions; (2) establish valid criteria for allocating functional activities between humans and machines; and (3) provide insight into the technology requirements, economics, and benefits of the human presence in space.

The study started in October of 1983 and was completed in September of 1984.

The final report has been prepared in three separate volumes:

Volume I - Executive Summary
Volume II - Research Analysis and Technology Report
Volume III - Generalizations on Human Roles in Space

This document is Volume II in the series. It is the technical report of the work accomplished and contains the data and analyses from which the study results were derived.

The study results are intended to provide information and guidelines in a form that will enable NASA program managers and decision-makers establish, early in the design process, the most cost-effective design approach for future space programs, through the optimal application of unique human skills and capabilities in space.

Questions and comments regarding this study or the material contained in this document should be directed to:

Stephen B. Hall
THURIS Study Manager
Code PD 24
National Aeronautics and Space Administration
George C. Marshall Space Flight Center
(205) 453-4196

(or)

Harry L. Wolbers
THURIS Study Manager
McDonnell Douglas Astronautics Company
Huntington Beach, California
(714) 896-4754

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Section 1
INTRODUCTION AND SUMMARY

The space project managers and engineers within NASA today are faced with a significant challenge. On the one hand, with the Shuttle's attainment of operational status, the nation's Space Transportation System (STS) has successfully completed one more step toward establishing the permanent presence of man in space. On the other hand, the competing demands on this nation's limited economic resources are forcing an increasing awareness of the need to maximize economic efficiency in achieving the goals and objectives of future space missions. To meet this challenge, a rational methodology and set of performance and cost criteria are critically needed by space project managers and decision makers if they are to design the most cost-effective man-machine systems to accomplish specific missions.

To be of value, these assessment procedures must clearly indicate to the decision maker the optimal location of each activity and functional operation along the continuum from direct human intervention and control to independent system operations.

As a point of reference, too often in system design an artificial dichotomy is created that attempts to classify systems as <u>manned</u> or <u>unmanned</u>. There is no such thing as an unmanned system: everything that is created by the system designer involves man in one context or another; everything in our human existence is done by, for, or against man. The point at issue is to establish in every system context the optimal role of each man-machine component.

To this end, the Human Role in Space (THURIS) Study has (1) investigated the role and the required degree of direct involvement of humans in future space missions; (2) established criteria for the allocation of functional activities between humans and machines; and (3) investigated the technology requirements, economics and benefits of the human presence in space. Six

basic categories of man-machine interaction were considered in the study. They were Manual, Supported, Augmented, Teleoperated, Supervised, and Independent modes of operation. These categories are defined in Figure 1-1.

Manual	Unaided IVA/EVA, with simple (unpowered) hand tools
Supported	Requires use of supporting machinery or facilities to accomplish assigned tasks (e g , manned maneuvering units and foot restraint devices)
Augmented	Amplification of human sensory-motor capabilities (powered tools, exo-skeletons, etc)
Teleoperated	Use of remotely controlled sensors and actuators allowing the human presence to be removed from the work site (remote manipulator systems, teleoperators, telefactors)
Supervised	Replacement of direct manual control of system operation with computer-directed functions although maintaining humans in supervisory control
Independent	Basically independent self-actuating, self-healing operations but requiring human intervention occasionally (automation and artificial intelligence)

Figure 1-1. Categories of Man-Machine Interaction

The study activity was organized into four task areas, as follows:

TASK 1 - HUMAN QUALIFICATIONS FOR SPACE ACTIVITIES

The objective of this task was to provide documented information on human capabilities and limitations in order to establish guidelines for defining the human role in manual, supported, augmented, teleoperated, supervised, and independent modes of system operation.

TASK 2 - SELECTED PROJECT ASSESSMENTS

The objectives of this task were (1) to analyze a representative set of space missions in order to identify a generic set of mission activities that may in turn be used as a catalog from which a selected number can be extracted as applicable to describe any future space mission (Subtask 2.1); (2) to develop typical timeline data and mission impact factors for each of the generic activities in order to be able to synthesize and compare the viable alternative options for accomplishing future mission objectives (Subtask 2.2); (3) to define the hardware and software support requirements associated with each activity implementation option to sufficient depth to allow cost data on the alternative modes of implementation to be developed (Subtask 2.3); (4) to

prepare comparative cost data associated with the provision, support, and use of various degrees of direct human involvement in future space missions (Subtask 2.4); and (5) to develop a methodology for evaluating in qualitative and quantitative terms the impact of varying degrees of human involvement on the effectiveness and economy of satisfying the requirements of future space projects (Subtask 2.5).

TASK 3 - TECHNOLOGY REQUIREMENTS

The objective of this task was to identify the requirements for the technological developments that enable and enhance the human role in space and to uncover gaps that will need to be considered in both ground-based research and development programs and in flight experiments, as appropriate.

TASK 4 - GENERALIZATIONS ON THE HUMAN ROLES IN SPACE

The objective of this task was to summarize (in an easily accessible procedural format) the methodology developed during the THURIS study for selecting the optimal mode of man-machine interaction in any specific system application. To accomplish this objective, the information generated in Task 1 - Human Qualifications for Space Activities, Task 2 - Specific Project Assessments, and Task 3 - Technology Requirements was used to develop a decision guide to assist space project managers in assessing the relative value of the various categories of man-machine interaction in meeting the activity requirements of future space systems.

The overall study flow is summarized in Figure 1-2.

In the following sections of this document, the analyses and data generated and the results obtained in each of these task areas is presented. Section 2 describes the Task 1 analyses, Section 3 describes the Task 2 analyses, Section 4 describes the Task 3 analyses and Section 5 describes the Task 4 analyses. Many different criteria can be suggested as candidates for inclusion in the decision process for allocating functional activities between humans and machines. As will be described in the following pages, the study team has concentrated on three principal indices: performance, cost, and technological readiness as an indicator of success probability.

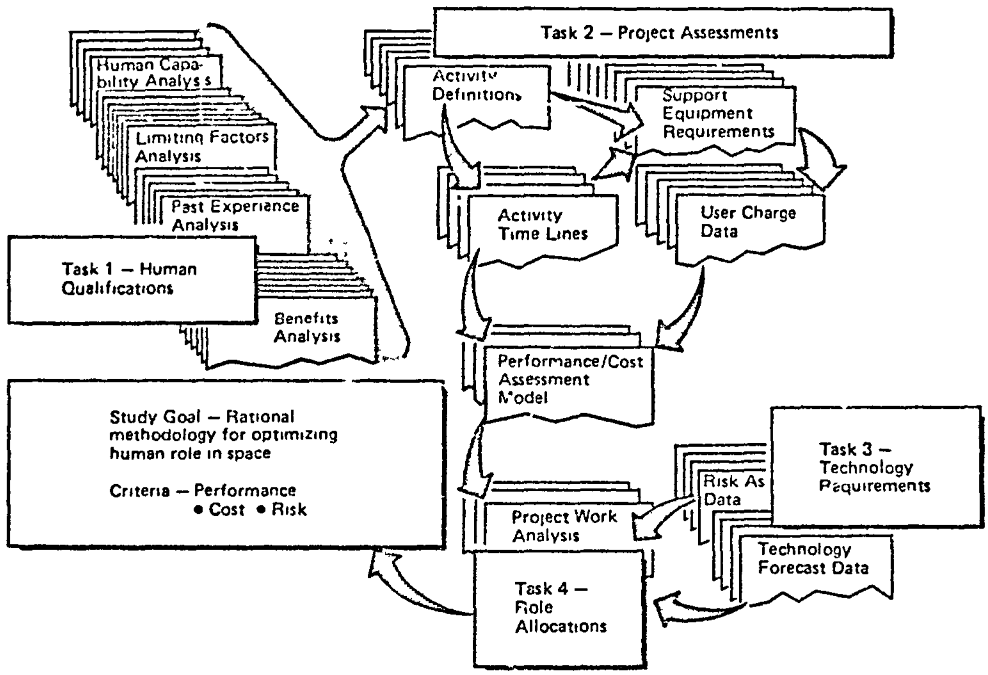


Figure 1-2. Study Methodology

With regard to performance, 37 generic classes of activities were defined (see Section 3) that, when combined in the required operational sequences, could be used to describe a broad spectrum of potential space programs. For each of these activities and for each category of man-machine interaction (manned, supported, augmented, teleoperated, supervised, and independent operations), the limiting factors in terms of sensing, information processing and motor actions have been defined and the requirements for human involvement have been described (see Section 2).

Some system operational requirements specify performance beyond human sensory or psychomotor capabilities (e.g., sensing outside the visible band of the electromagnetic spectrum, force actuation beyond normal human capability, or exposure to extreme pressure, temperature, or toxic environments). As a general rule, however, response time was found to be the most generally applicable discriminator between the manually controlled modes and the supervised and independent modes of operation. If responses in time periods of seconds or less are required, then the activity is generally best performed

in the supervised or independent modes. Applications where speed of response would dictate that the activities be performed in the supervised or independent modes might include launch abort procedures and orbital trajectory corrections. If allowable response times become minutes or hours, then all modes might be applicable and the criteria of cost effectiveness or technological readiness would provide the more appropriate basis for selection of a particular mode of implementation.

With regard to cost, costing models were derived (see Section 3) that provided comparative data on the relative costs for each man-machine mode in performing each activity, from one to many hundreds of times. It was found that some system operational requirements are of such a low demand that the development of automated systems becomes prohibitively expensive in view of the benefits achieved. These comparative costing data were further refined to take into acount the commonality that can exist among the equipment items or resources needed to support multiple activities.

With regard to technological readiness, it was found by the study team that the level of readiness could provide another useful metric in the role allocation decision process. The higher the technological readiness level of a given man-machine implementation concept, the more confidence the decision-maker would have that the mission objectives could be met within time and budget. In other words, the higher the readiness level, the higher will be the probability of mission success.

For programmatic planning purposes, the schedule risk in meeting program milestones is directly dependent upon the readiness level. It was found that the time scale required to achieve a given level of technological readiness depends in turn upon the degree of complexity of the system to be developed. For relatively simple systems, the times required to move from concept to operational readiness may take from 1 to 5 years. This time range often reflects the impact of factors other than technical progress on the development process, such as political or budgeting constraints or the availability of corollary systems required to demonstrate or aid in the development of the item in question. The time requirement for a more complex system may take even longer.

Based upon the analysis described in Sections 2, 3, and 4, a decision guide was formulated that can be used to logically allocate space activities to alternative man-machine implementation modes based upon the criteria of performance, cost and technological readiness as developed in Tasks 1, 2, and 3 of the study. Such a guide might take many forms. One procedural approach that appears promising, however, utilizes a worksheet format and is described in Section 5.

Section 2

HUMAN QUALIFICATIONS FOR SPACE ACTIVITIES - TASK 1

The objective of Task 1 was to provide information on human capabilities and limitations and on their application to space mission tasks. This was accomplished by compiling data on a large number of basic and unique human capabilities, defining the limiting factors relevant to these capabilities, and by documenting historical precedents and past experience from various U.S. and Russian space mission reports.

2.1 HUMAN CAPABILITY DATA

A detailed list of human capabilities applicable to space mission activities was compiled from previous studies, human factors texts, and biomedical references. For simplification purposes these capabilities were grouped into three categories: Sensory/Perceptual; Intellectual; and Psychomotor/Motor. A list of the capabilities examined under each of these three categories is presented in Table 2-1.

For each capability, a definition was provided, its characteristics were identified, factors which tend to change or limit the capability were listed, and comments were made regarding the relevance and application of the capability to man's role in space. This data is summarized for each of the basic human capabilities in Appendix A.

While considerable quantitative data were found in the literature defining sensory discrimination abilities and the fine and gross motor responses that humans are capable of making, the higher level cognitive functions are not as precisely defined in terms that can be used directly by system engineers. To address this problem of defining the "intelligent" operations of the human element in man-machine systems, we have borrowed the terminology proposed by the eminent psychologist, J. P. Guilford, in his "Structure-of-Intellect" model. In examining the nature of human intelligence, Guilford defines the dimensions of intelligence in terms of Cognition, Memory, Divergent Production, Convergent Production and Evaluation.

Table 2-1
BASIC HUMAN CAPABILITIES

A. Sensory/Perceptual and Capabilities

- Visual Acuity
- Brightness Detection and Discrimination
- Color Discrimination
- Depth Perception and Discrimination
- Peripheral Visual Detection and Discrimination
- Visual Accommodation
- Detection and Discrimination of Tone
- Discrimination of Sound Intensity
- Sound Localization
- Detection of Light Touch
- Tactile Recognition of Shape and Texture
- Discrimination of Force Against Limb
- Discrimination of Limb Movement and Location
- Detection and Discrimination of Angular Acceleration
- Equilibrium
- Detection and Discrimination of Vibration
- Detection of Heat and Cold
- Detection and Discrimination of Odors

B. Intellectual Capabilities

- Cognition
- Memory
- Divergent and Convergent Production
- Evaluation

C. Psychomotor/Motor Capabilities

- Production and Application of Force
- Control of Speed of Motion
- Control of Voluntary Responses
- Continuous-Adjustment Control (Tracking)
- Arm/Hand/Finger Manipulation
- Body Positioning

Cognition is defined as awareness, immediate discovery or rediscovery, or recognition of information in various forms: comprehension or understanding. Information acted upon by the human element can be in the form of figures, symbols, semantic units, behavioral units, classes, relations, systems and transformations.

The terms cognition and perception overlap to some degree. Both perception and cognition are concerned with input information from sensory

sources. Perception, however, is concerned primarily with sensory properties and with the cognition of figural units. The complete cognitive process includes operation with symbolic, semantic, and behavioral concepts as well. Perception is midway along a continuum extending from sensing at one end to thinking at the other. It is the process of organizing and interpreting sensory inputs based upon past experience. Cognition involves a broader range of mental acivity including awareness of semantic meaning and abstract concepts.

Memory is defined as information retention or storage, with some degree of availability of information in the same form in which it was committed to storage and in connection with the same cues with which it was learned. Memory is distinguished from cognition per se by the ability to recall information having once been exposed to the information. Memory storage, however, is an essential condition or determiner of cognition.

Divergent Production can be defined as the generation of new information from given information where the emphasis is on variety and quantity of output from the same source. Divergent Production is related to creative imagination. In this process, items of information are retrieved from memory storage and used to generate a number of varied responses.

Convergent Production is defined as the derivation of logical deductions or at least compelling inferences leading to a unique answer or conclusion. In convergent production the problem can be rigorously structured, and is so structured, and an answer is forthcoming without much hesitation.

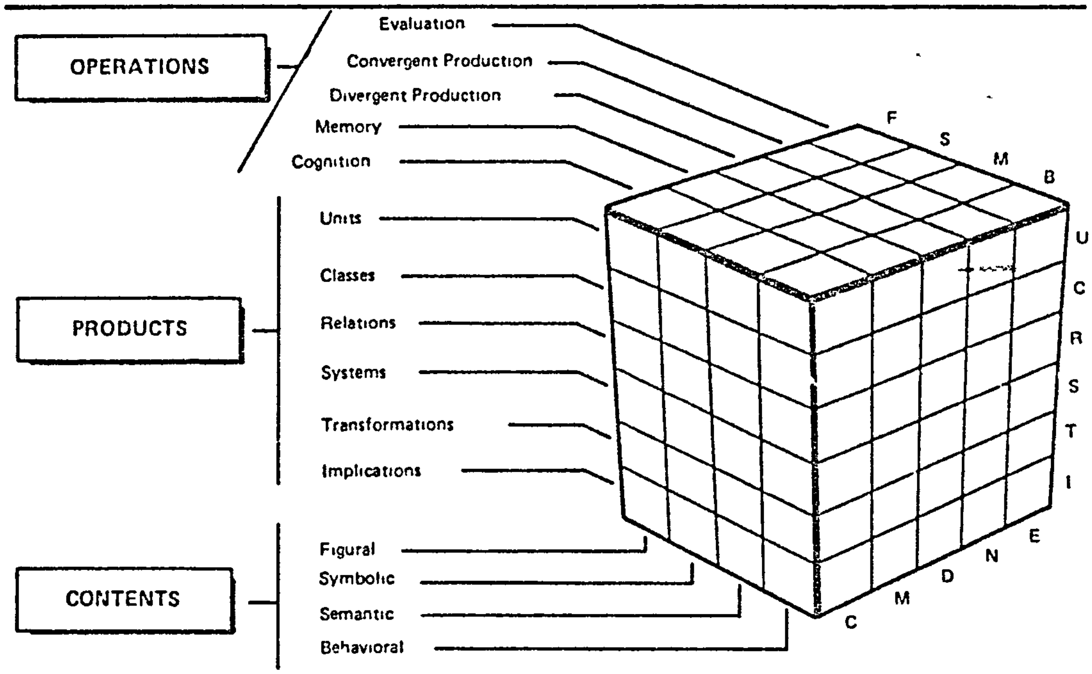
Evaluation is defined as a process of comparing a product of information with known information according to logical criteria and making a decision concerning criteria satisfaction.

Planning and scheduling activities, monitoring flow patterns, target recognition, understanding speech patterns, etc., are examples of the cognitive operations that will be required in future space systems. In the understanding of speech, for example, peak clipping of the signal causes considerably less intelligibility loss than center clipping. Understanding

the relative level of cognitive capabilities of humans in recognizing information in alternative forms permits the system designer to select the most efficient design approach for meeting mission objectives. Memory for procedures, target characteristics, etc., will be essential in long duration space missions as will the Divergent Production operations in problem solving, development of alternative courses of action, and improvising in emergencies. Convergent Production operations are required in trouble-shooting tasks and Evaluation operations will be essential for assessing the level of normal or abnormal performance of system elements and, through comparative judgments of "greater than," "less then," or "equal to," to direct system operations in the most expeditious manner.

Historically there seems to have been a belief that these "mental" operations are the same whether they are performed with verbal-meaningful information or with visual-figural information. In fact this is not true. Extensive factor-analytical results have proved wrong the belief that the same ability is involved regardless of the kind of information with which we deal. Using hundreds of tests of mental activity, Guilford has demonstrated over forty intellectual factors. These factors are related to tasks involving the processing of different types of information ranging from figures or pictures, to symbols such as letters or numbers, to using words in speaking or reading, to responding to the nonverbal interactions in the behavior of other people. Tasks may also require doing different things with the information such as predicting or anticipating outcomes; transforming the information from one form to another; organizing or structuring the information into a meaningful aggregate, recognizing or establishing relationships between two or more items by virtue of their common properties, or dealing with individual units or items of information having unique characteristics. Accordingly, the description of intelligent behavior must allow for the interrelationships of information content and the products of the intellectual activity witn the basic operations themselves (i.e., Cognition, Memory, Divergent Production, Convergent Production, and Evaluation).

This multidimensional model of human intellectual activity can be visualized as shown in Figure 2-1, where each cell in the multidimensional matrix represents a potentially unique intellectual activity. If intellectual



Adapted From Guilford, J P The Nature of Human Intelligence, McGraw-Hill, New York, 1967

Figure 2-1. The Structure of Intellect

abilities and activities can be described in terms of this "Structure of Intellect" model, and if tasks to be performed in advanced space systems can be analyzed in terms of these same categories, a powerful tool becomes available for defining the intellectual role of the human in system operations.

Mission activities will benefit to a greater or lesser extent by the direct, onboard participation of man. Of the list of basic human capabilities summarized in Table 2-1, seven clusters of capabilities are considered key for establishing the extent of man's direct participation in space activities (see Figure 2-2). These key capability clusters are those that should serve as the basis for the selection of the human to perform a function rather than allocating the function to a machine; they are those on which the product of the activity will be directly dependent. The following is a list of the key capability clusters, with a discussion of their characteristics and importance.

Visual Capabilities. Although specific visual capabilities, such as visual acuity and depth perception, can be measured and assessed individually,

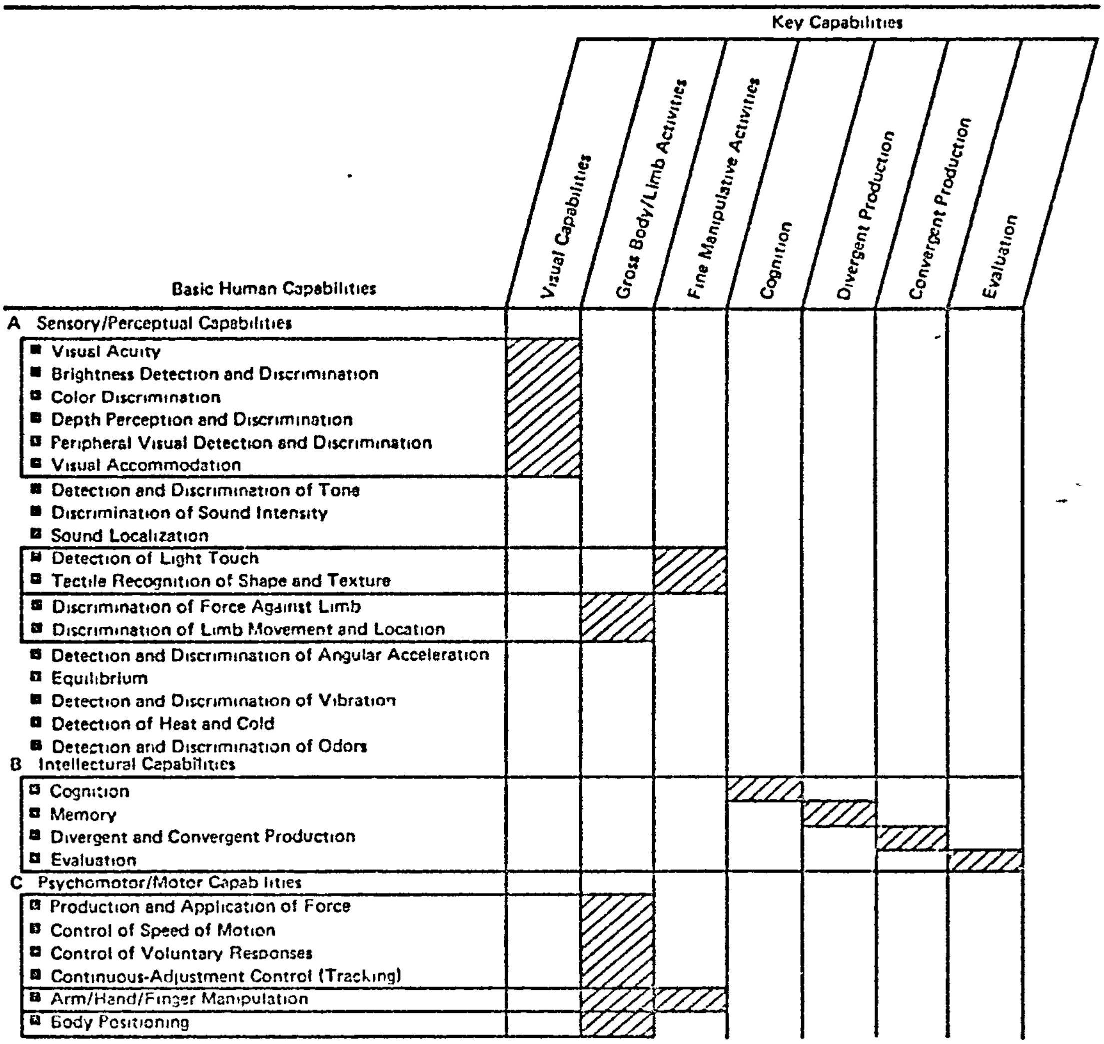


Figure 2-2. Key Capabilities

almost all are used in concert in tasks requiring observation and inspection. Visual capabilities were, therefore, considered as a unit capability in this evaluation.

Man would be selectively chosen for tasks requiring visual evaluations, when visual capabilities were combined with intellectual capabilities, particularly when a subsequent action is dependent on the evaluation. Examples of such tasks include earth observations and laboratory examinations of specimen characteristics either unaided or with the use of a microscope.

Gross Body/Limb Activities. Similar to visual capabilities, numerous individual capabilities are used in concert, without distinction, in tasks requiring the use of arms, legs, and body torso for their conduct. For this reason a number of psychomotor/motor capabilities such as arm/hand/finger control of force, arm/hand/finger control of speed of motion, and body positioning were combined into the key capability of gross body/limb activities.

Man would be selectively chosen on the basis of this key capability for such applications as complex structural assembly involving infrequently repeated functions, and subsystem maintenance particularly when troubleshooting was involved requiring the use of convergent production or other intellectual capabilities in concert with gross body/limb activities.

Fine Manipulative Activities. This key activity is supported by numerous sensory modalities such as detection of light touch and tactile recognition of shape and texture; it is the fine manipulative activities, however, that directly satisfy task objectives. Fine manipulative activities when applied to such functions as animal surgery and dissection and complex assembly and repair at a workbench usually cannot be duplicated by automated devices. Man, therefore, is usually essential in most tasks requiring this key capability.

Man's greatest assets with respect to his participation in space ativities are his intellectual capabilities, most particularly cognition, divergent production, convergent production, and evaluation. Man's memory, of all intellectual capabilities, is the one most easily duplicated and surpassed by computer activities. Although man's memory does have some unique characteristics which support and reinforce the other intellectual capabilities, in space activity planning, man would seldom be selectively chosen on the basis of his memory alone. The other intellectual capabilities are, however, unique and are the primary reasons for the human role in space.

Cognition. Vital to all activities requiring information processing and interpretation.

Divergent Production. Essential to all tasks requiring a creative or innovative approach; plays a unique role in the utilization of man in space activities.

Convergent Production. Of value to tasks, such as maintenance troubleshooting, requiring logical deductions.

Evaluation. Essential to such tasks as laboratory analyses and the engineering evaluation of extravehicular technology experiments.

The remainder of the capabilities listed in Table 2-1 are normally utilized in either an ancillary mode supporting the key capabilities, or they are made use of by the task designer when designing the man-machine interface. Illustrative examples of the use of ancillary-capabilities include the support that fine manipulative activities receive from tactile capabilities or the use of auditory capabilities to receive sound signals or alarms in a particular task design.

The limits of human capabilities may be altered by both environmental and task-related factors. Among the most commonly examined factors are atmospheric stresses--hostile changes in the individual's ambient, breathing atmosphere. Six such stresses are identified in Figure 2-3. The severity of the effect of each stress is dependent upon both the intensity of the variation and the duration of the exposure. Each of the stresses indicated is capable of producing unconscicusness or death with the appropriate combination of duration and intensity. The indicated values are those generally

Type of Stress	Concentration/Intensity of Stress	
	Performance Degrading	Injurious or Life Threatening
Decreased O_2 (hypoxia)	P_{O_2} ~ 109 mm Hg	P_{O_2} ~ 73 mm Hg
Increased O_2 (O_2 toxicity)	P_{O_2} ~ 400 mm Hg	P_{O_2} ~ 1500 mm Hg
Increased CO_2 (hypercapnia)	P_{CO_2} ~ 20 mm Hg	P_{CO_2} ~ 45 mm Hg
Increased temperature (hyperthermia)	~ 95°F	~ 120°F
Decreased temperature (hypothermia)	~ 50°F	~ 39°F
Atmospheric contamination (e g , CO)	~ 25 ppm CO	~ 400 ppm CO

Figure 2-3 Limiting Factors – Effects of Atmospheric Stresses on Human Performance

considered to be the least intense that will produce either performance degradation or injury with unlimited exposure.

Atmospheric stresses are usually compensated for by ECLS systems, either in the spacecraft or associated with the EMU in EVA. Because of this, atmospheric stresses do not commonly restrict activities, but they do add to the cost of utilizing man.

The human is susceptible to environmental stresses other than atmospheric and these other stress factors, like atmospheric stresses, may reach intensities that can produce injury or death. Stresses of the type indicated in Figure 2-4 are not as subject to being counteracted as are variations in atmospheric characteristics and are usually avoided by specific approaches to spacecraft design characteristics or mission operations.

The Space Adaptation Syndrome (SAS) or space motion sickness has occurred to some degree on all U. S. space flights since Mercury and Gemini. In addition, 49 percent of the Russian cosmonauts have reported the condition. The symptoms are generally the same as those asociated with conventional motion sickness. They occur early in flight, peak at about 24 to 36 hours, but may last as long as four days.

The occurrence of SAS cannot be predicted in any given individual. Once adaptation has occurred in flight, however, and it always does, the individual is exceptionally resistant, even to challenging exposures, for the rest of the flight and for a week or more postflight.

Type of Stress	Intensity of Stress	
	Performance Degrading	Injurious or Life Threatening
Vibration	0 03 g s at ~ 4 to 8 Hz	2 g's at ~ 3 to 8 Hz
Noise	80 to 85 dB	100 to 120 dB
G_Z acceleration	2 to 3 g s	5 to 6 g s
G_X acceleration	5 to 6 g's	12 to 15 g's
Light	Complex	2 4 x 10^5 lumens/ft^2
Ionizing radia ion	–	> 5 rads/day

Figure 2 4. Limiting Factors – Effects of Other Environmental Stresses on Human Performance

The extent to which SAS degrades crew performance has not been measured with any accuracy or precision. There is some evidence that dedicated, well-trained crew members will perform successfully despite the effects of SAS. On the other hand, some activities on previous missions have been postponed or cancelled because of SAS. Figure 2-5 summarizes previous SAS experience on U. S. spaceflights. More definitive information on the effects of SAS or prevention procedures are not likely to be released in the immediate future since all such crew data are now considered NASA-proprietary.

Human Capabilities Impacted	Duration of Exposure (hours)						
	< 3	3 12	12 24	24 48	48-72	72 96	> 96
Vision	None	Mod	Mod	Neg	Neg	None	None
Discrimination	None	Mod	Mod	Neg	Neg	None	None
Discrimination of angular acceleration	Neg	Mod	Sig	Sig	Sig	Sig	Sig
Cognition	None	Mod	Sig	Sig	Mod	Neg	None
Memory	None	Neg	Neg	None	None	None	None
Evaluation	None	Mod	Sig	Mod	Neg	None	None
Visual motor tracking	Mod	Sig	Sig	Mod	Neg	Neg	None
Manipulative skills	None	Mod	Sig	Sig	Mod	Neg	None
Body positioning	Mod	Sig	Sig	Mod	Mod	Neg	None

Impact Code (Decrease in observed capability)	
None	(None)
Negligible	(Neg)
Moderate	(Mod)
Significant	(Sig)

Figure 2-5 Limiting Factors — Space Adaptation Syndrome (Exposure to Weightlessness)

2.2 HISTORICAL PRECEDENTS AND PAST EXPERIENCE

It is one thing to arrive at a conclusion regarding the capabilities or limitations of the human for participating in a mission activity on the basis of empirical laboratory data and deductive reasoning; it is quite another to be able to cite specific examples, taken from previous spaceflight experience, of the astronaut accomplishing precisely what it was predicted that he or she could do. To identify crew operations and activities from prior space missions that could be used to illustrate the human capability to perform effectively in an actual mission situation, we examined a large number of documents from various sources. These included reports published in technical journals, such as Aviation, Space, and Environmental Medicine, Aviation Week and Space Technology, and Spaceflight; NASA Mission Reports; STS Mission

Debriefings; Experiment Operations Handbooks; and symposia reports. These information sources were supplemented by information obtained from debriefing interview tapes of the Spacelab One mission and a with personal interview of an astronaut (Owen K. Garriott) who participated in both the Skylab and the Spacelab missions (see Appendix B). Study team members were also present in the Mission Operations Control Center to observe crew performance during the STS Flight 41-C (Solar Max Repair Mission).

Examples of human activities in space operations were selected from Skylab, STS, Spacelab, Salyut, and Soyuz missions and are summarized in Table 2-2. They consist of the specific mission activity, the general crew activities involved, comments on important aspects of the operation, and the name of the source document from which the information was derived. This listing is not meant to be all-inclusive but rather it is intended to provide examples of the range of crew activities that are possible in future space missions.

Many other specific examples could have been cited. On Skylab, for example, the crew performed servicing operations that were never originally planned or intended to be done in orbit. Leaks in the airlock module cooling loops resulted in a condition where Coolanol fluid had to be added. If service ports had been provided in the system, it would have been a simple matter to replace the fluid. As it was, the crew had to install a saddle clamp and puncture a line in order to add Coolanol to the system. This potentially important role of the flight crew on a space vehicle is typified by the comments, general impressions, attitude and behavior of the first Skylab crew who are quoted as stating, "We can fix anything given the proper tools in space that we can fix on the ground." The experience by all three crews demonstrated clearly that man is the key link in enhancing mission success by retaining, or restoring to service, critical functions. To do this the man must have access in both EVA and IVA operations.

One of the biggest problems in the Skylab EVA repair operations was the lack of EVA restraint devices. One of the very important lessons learned from Skylab about EVA operations was that the crew needed the ability to get to any place on the outside of the vehicle for repair jobs. An important groundrule

Table 2-2. Historical Precedents/Experiences as Observed in Previous Manned Mission Activities (Page 1 of 8)

DOCUMENT	MISSION ACTIVITY	INCLUDED GENERIC ACTIVITIES	COMMENTS
Aerospace Medical Assoc. May 1974 Annual Meeting Report	• Skylab's Apollo Telescope Mount (ATM) film canister film magazine retrieval and resupply	• Position module • Remove module • Remove/replace covering • Transport loaded • Release/secure mechanical interface	• Skylab's Apollo Telescope canister required EVA to remove, replacement and retrieval of film cameras/magazines • Routine EVA
Skylab Experience Bulletin #1 June 1974	• Opening of observation windows in Multiple Docking Adapter (MDA)	• Release/secure mechanical interface • Remove/replace covering	• Crew encountered higher than expected torque on window latch mechanism • No provided foot or body restraint to counteract applied torque • Crewman wedged body against wall structure
Skylab Experience Bulletin #5 September 1974	• Corrective action during first EVA to repair camera door that had failed to remain open	• Define procedures/schedules/operations • Implement procedures/schedules • Inspect/observe • Remove/replace covering	• Door latching mechanism over-ridden • Door pinned in open position
Skylab Experience Bulletin #5 September 1974	• Deployment of sunshade on Skylab 3 OWS, EVA	• Adjust/align elements • Confirm/verify procedures/schedules/operations • Gather/replace tools/equipment • Implement procedures/schedules • Release/secure mechanical interface • Remove/replace covering • Transport loaded	• Required to erect a thermal shade down the side of orbital workshop • Required to assemble two 55 ft poles (11 pieces per pole), endless clothesline attached to each assembled pole • Two crewmen performed repair activity • One crewman anchored at ATM structural strut • One crewman positioned at EVA hatch • EVA hatch crewman assembled segmented poles and passed poles and line to second EVA crewman • Poles positioned and attached to OWS structure • Thermal shade attached to secured poles • EVA repair activity was successful and accomplished with minimal training
Skylab Experience Bulletin #5 September 1974	• EVA deployment of damaged Skylab solar array wing	• Deploy appendage • Detect change in state or condition • Adjust/align elements • Gather/replace tools/equipment • Implement procedures/schedules • Problem solving/decision making/data analysis • Release/secure mechanical interface • Remove/replace covering • Transport loaded	• Skylab 1 solar array did not deploy • Skylab 2 went EVA to cut debris strap and erect solar array wing • Task accomplished despite lack of specific contingency activity
Skylab Experience Bulletin #5 September 1974	• Requirement to clean contaminated camera lens (EVA)	• Replace/clean surface coatings • Gather/replace tools/equipment • Inspect/observe	• Camera lens found to have debris from Skylab launch thrusters • Cleaned during EVA
Skylab Experience Bulletin #5 September 1974	• Requirement to repair tilt and rotation gear jam on corollary experiment S019	• Activate/initiate system operation • Deactivate/terminate system system operation • Confirm/verify procedures/schedules/operations • Gather/replace tools/equipment • Implement procedures/schedules • Problem solving/decision making/data analysis • Remove/replace covering	• Gear jam of experiment S019 • Required to open gear box to free gear

Table 2 2. Historical Precedents/Experiences as Observed in Previous Manned Mission Activities (Page 2 of 8)

DOCUMENT	MISSION ACTIVITY	INCLUDED GENERIC ACTIVITIES	COMMENTS
Skylab Experience Bulletin #5 September 1974	• Requirement to replace failed blood pressure cuff on medical experiment M092	• Apply/remove biomedical sensor • Connect/disconnect electrical interface • Activate/initiate system operation • Deactivate/terminate system operation • Release/secure mechanical interface	• Blood pressure cuff on M092 experiment failed • Cuff portion of experiment was removed and replaced with spare cuff carried on board
Proceedings of the Skylab Life Sciences Symposium NASA-JSC Report JSC-09275 November 1974	• Conduct of experiment M131, Human vestibular function (Skylab II, III, and IV)	• Communicate information • Correlate data • Store/record elements • Activate/initiate system operation • Adjust/align elements • Apply/remove biomedical sensors • Deactivate/terminate system operation • Detect change in state or condition • Gather/replace tools/ juipment • Implement procedure· chedules • Position module • Remove module	• Experiments conducted in rotating litter chair • Experiment included 3 different tests Oculogyral Illusion Test, Motion Sensitivity Test, Special Localization Test • All Skylab crewmen served as both subject and observer for experiments
Proceedings of the Skylab Life Sciences Symposium NASA-JSC Report JSC-09275, November 1974	• Conduct of experiment M171, metabolic activity (Skylab II, III, and IV)	• Display data • Activate/initiate system operation • Adjust/align elements • Apply/remove biomedical sensor • Connect/disconnect electrical interface • Deactivate/terminate system operation • Gather/replace tools/equipment • Implement procedures/schedules • Insp·ct/observe • Record/store element • Release/.ecure mechanical interface	• Experiment was performed on all manned Skylab missions • Experiment designed to determine changes in metabolic activity, heart rate, and blood pressure during exercise in weightlessness • All crewmen on all missions functioned as both observers and subjects
Proceedings of the Skylab Life Sciences Symposium NASA/JSC Report JSC-09275, November 1974	• Conduct of experiment M172, Body mass measurement (Skylab II, III, and IV)	• Compute data • Activate/initiate system operat'cn • Adjust/align elements • Communicate information • Deactivate/terminate system operation • Display data • Implement procedures/schedules • Inspect/observe • Position module • Record elements • Remove module	• Mass measured in oscillating chair called Body Mass Movement Device (BMMD) • Time, BMMD temperature, and oscillation period recorded in log for each experiment and communicated to ground • All Skylab crewmen performed experiment
Proceedings of the Skylab Life Sciences Symposium NASA-JSC Report JSC-09275 November 1974	• Inflight blood collection (Skylab II, III, and IV)	• Allocate/assign/distribute • Surgical manipulations • Activate/initiate system operation • Deactivate/terminate system operation • Gather/replace tools/equipment • Implement procedures/schedules • Position modules • Remove module • Store/record elements	• Blood samples were transferred to Automatl. Sample Processors (ASP's) centrifuged, and stored in freezer • Blood samples were acquired on all maned Skylab missions and supported several experiments
Aviation Week and Space Technology 24 February 1975	• Requirement to spray a new reflective layer on the receiving and focusing mirrors of the Salyut's solar telescope (Soyuz 17/Salyut 4)	• Activate/initiate system operation • Confirm/verify procedures/ schedules/operations • Deactivate/terminate system operation • Inspect/observe • Replace/clean surface coating	• This operation was apparently done by remote control • Condensed vapor and tiny particulate matter tend to collect on the optics thus affecting instrument performance
Aviation Week and Space Technology 30 June 1975	• Requirement for cosmonauts to manually position the solar telescope due to a malfunction of the instruments pointing system, thus salvaging their solar research experiments (Soyuz 17/Salyut 4)	• Pursuit tracking • Adjust/align elements • Compute data • Confirm/verify procedures/ schedules/operations • Inspect/observe • Problem solving decision making/ data analysis	• The crew had to position the station so as to direct the telescope's axis at the center of the solar disk • The crew used the stethoscope from the medical supplies to more accurately monitor the rotating mirrors movements in the support structure

Table 2-2. Historical Precedents/Experiences as Observed in Previous Manned Mission Activities (Page 3 of 8)

DOCUMENT	MISSION ACTIVITY	INCLUDED GENERIC ACTIVITIES	COMMENTS
Spaceflight Vol 18, No 1 January 1976	• Requirement to repair TV camera on Soyuz 19 (Soyuz 19/Apollo ASTP July 1975	• Activate/initiate system operation • Implement procedures/schedules Inspect/observe • Problem solving/decision making/data analysis • Release/secure mechanical interface • Remove/replace covering	• Soyuz 19 experiences T.V. camera malfunction • Repair accomplished and camera put back into operation
Spaceflight Vol 19, No 4 April 1977	• Augmentation of automatic satellite weather information by visual observation from Salyut 5 (Soyuz 21/Salyut 5 July 1976)	• Information processing • Communicate information • Inspect/observe • Problem solving/decision making/data analysis	• Soyuz 21 crew requested supplement weather observations received from unmanned weather satellite • Observations made accurately predicted storm/weather conditions not obtainable by automatic equipment
Spaceflight Vol 19, No 5 May 1977	• Soyuz 23 (Oct 76) automatic docking failed with Soyuz 24 (Feb 77) manual docking achieved	• Adjust/align elements • Confirm/verify procedures/schedules • Correlate data • Deactivate/terminate system operation • Detect change in state or conditions • Information processing • Pursuit tracking	• Soyuz 24 docked manually with Salyut 5 • Soyuz 23 was "frustrated" (failed) with its automatic docking system in earlier attempt
Spaceflight April 1978 Vol 20 No 4	• Resupply of Salyut 6 • Progress 1 docks with Salyut 6 (Jan 78) Unmanned supply craft docked automatically	• Replenish materials • Activate/initiate system operation • Confirm/verify procedures/schedules/operations • Deactivate/terminate system operation • Release/secure mechanical interface • Remove/replace covering • Transport loaded	• Remote control transport vehicle Progress 1 (developed from Soyuz spacecraft) successfully docks with Salyut 6 • The automatic spacecraft, based on the manned spacecraft Soyuz, according to Novosti is intended for transport operations to ensure long-functioning of orbital space stations "Aim of the launching is to carry out tests and comprehensive optimization of the design of the on-board systems and equipment, to exercise docking with the orbital manned complex Salyut 6/Soyuz 27, to deliver for the complex fuel for its power units and different cargoes, equipment, apparatus and materials for life-support of crew and for scientific exploration and experiments " (Operation is reminiscent of the 90-day docking exercise carried out between the unmanned Soyuz 20 and Salyut 4 between 17 Nov 1975 and 16 Feb 1976) • Crew manually transferred supplies from Progress I to Salyut 6. • Progress I delivered "fuel, equipment and supplies", vehicle then filled with waste, undocked, de-orbited and allowed to burn up in the atmosphere
Spaceflight June 1978 Vol 20 No 6	• EVA inspection and repair (Salyut 6 EVA, Dec 77, first Soviet EVA since 1969)	• Adjust/align elements • Activate/initiate system operation • Communicate information • Gather/replace tools/equipment • Inspect/observe • Remove/replace covering • Transport loaded	• EVA objective to inspect "outward elements" of Salyut, to check faulty docking unit, perform repair work as necessary • Voice link and hand held color TV camera utilized on EVA • Hand tools used to check and adjust equipment as necesary • "Semi-rigid" space suits utilized
Spaceflight August 1978 Vol 20 No 8	• General work performance in weightlessness (Skylab II)	• Information processing • Problem solving/decision making/data analysis	• Re Adaptation to Zero-g Interview with Dr Joseph P. Kerwin Skylab II science pilot • Adapted to zero-g in 7 to 10 days • All Skylab crew members middle aged

Table 2-2. Historical Precedents/Experiences as Observed in Previous Manned Mission Activities (Page 4 of 8)

DOCUMENT	MISSION ACTIVITY	INCLUDED GENERIC ACTIVITIES	COMMENTS
			• Physiology was very stable-adapted well to weightlessness • "Marvellous feeling, some uncomfortable aspects, stuffy nose, sleepy at times " • No impact on, or impairment of, mental functions
Spaceflight March 1979 Vol 21 No 3	• General performance in weightlessness (Soyuz 30/ Salyut 6)	• Information processing • Problem solving/decision making/data analysis	• Re Adaptation to Zero-g Joint USSR & Polish effort (crew) • Adapatation time confirmed, "first day" defined as negative "well being " • Reported as "Our day has been strenuous, because on the first day of adaptation to weightlessness our sense of well-being has to improve, but work must not suffer Today we were engaged on medical and biological research and checked on the filling with blood of the vessels of the brain and various parts of the body Then we conducted technological experiments Apart from that it was necessary to transfer all the equipment which Soyuz 30 had brought to the Salyut 6 orbiting station."
Spaceflight July 1979 Vol 21 No 7	• Requirement to purge defective fuel tank (Soyuz 32/Salyut 6/ Progress April 1979)	• Connect/disconnect fluid interface • Communicate information • Confirm/verify procedures/ schedules/operations • Deactivate/terminate system operation • Detect change in state or condition • Implement procedures/schedules • Release/secure mechanical interface • Remove/replace covering	• Soyuz 32/Salyut 6 required purge of defective fuel tank • Defined as perforate blatter separating nitrogen gas from fuel • Revolve entire space station complex about common center of gravity to aid in emptying fuel tank • Transfer fuel to other two tanks • Vent empty tank to space and purge with nitrogen
Spaceflight October 1979 Vol 21 No 11	• Deployment of erectable "umbrella" antenna (Salyut 6/Progress 9)	• Activate/initiate system operation • Adjust/align elements • Communicate information • Confirm/verify procedures/ schedules/operations • Deploy/retract appendage • Detect change in state or condition • Implement procedures/schedules • Problem solving/decision making/data analysis	• Salyut 6 antenna failed to deploy automatically • Ground control utilized Progress 9 (unmanned cargo craft) TV cameras to determine problem • Remote control of the radio telescope movement and the erection of its antenna was achieved from ground control
Spaceflight April 1981 Vol 23 No 5	• Planned repair, maintenance and scientific experiments (Soyuz T-4/Salyut 6/ Progress 12)	• Decode/encode data • Activate/initiate system operation • Allocate/assign/distribute • Confirm/verify procedures/ schedules/operations • Deactivate/terminate system operation • Display data • Implement procedures/schedules	• Soyuz T-4 crew (2) programmed for repair & maintenance of Salyut 6 as Salyut 6 is "not quite the last of the series" • Space factory experiments also planned
STS-1 Orbiter Mission Report JSC 17378 August 1981	• Manual control of flow valves to obtain cabin warm air (STS-1)	• Adjust/align elements • Information processing • Inspect/observe • Problem solving/decision making/data analysis	• During first sleep period cabin warm air system failed to respond • Temperatue selector set at - 45% 85% - 52% - 0% • System did not respond until crew "pinned" the exchanger bypass valve in the full warm position

Table 2-2. Historical Precedents/Experiences as Observed in Previous Manned Mission Activities (Page 5 of 8)

DOCUMENT	MISSION ACTIVITY	INCLUDED GENERIC ACTIVITIES	COMMENTS
STS-1 Orbiter Mission Report JSC 17378 August 1981	• Actuation of override control to open shutter on star tracker (STS-1)	• Confirm/verify procedures/schedules/operations • Define procedures/schedules/operations • Implement procedures/schedules • Problem solving/decision making/data analysis	• Star tracker shutters not cycling open and closed as expected • Crew analyzed problem, shutter not responding to auto control • Manual override of shutter by crew solved problem
Spaceflight October 1981 Vol No	• Crew observations of climatic zones for the benefit of agriculture (Salyut 6)	• Communicate information • Information processing • Inspect/observe • Problem solving/decision making/data analysis • Pursuit tracking	• The flight began at the time of sowing and ended just after the harvest • The crew monitored the progress of the growing season and spoke to experts in forestry, glaciology, agriculture and other disciplines • The crew very accurately predicted harvest yields in various growing areas
Spaceflight October 1982 Vol No	• Emergency repair on the Elena-F gamma-ray detector (Salyut 6)	• Precision manipulation of objects • Inspect/observe • Problem solving/decision making/data analysis • Release/secure mechanical interface	• When the detector malfunctioned, the crew was able to disassemble the unit, fashion a pin to replace the malfunctioned part and reassemble it
STS 2 Orbiter Mission Report JSC 17959 February 1982	• CRT replacement (STS-2)	• Activate/initiate system operation • Adjust/align elements • Connect/disconnect electrical interface • Deactivate/terminate system operation • Gather/replace tools/equipment • Implement procedures/schedules • Position module • Release/secure mechanical interface • Remove module • Store/record element	• Display unit #1 CRT failed during on-orbit operations • Crew removed failed unit • Crew replaced failed unit with display unit from aft station
STS-1 Orbiter Mission Report JSC 17959 February 1982	• Reset of open RMS TV circuit breaker (STS-1)	• Activate/initiate system operation • Connect/disconnect electrical interface • Inspect/observe • Problem solving/decision making/data analysis	• During day-2 RMS operations, the RMS wrist/elbow TV camera circuit breaker opened • Crew reset breaker • Resetting breaker did not solve problem • Trouble shooting isolated problem to excessive current draw by elbow
STS-3 Orbiter Mission Report JSC 18348 June 1982	• CRT keyboard switch replacement (STS-3)	• Activate/initiate system operation • Confirm/verify procedures/schedules • Connect/disconnect electrical interface • Deactivate/terminate system operation • Define procedures/schedules • Position module • Problem solving/decision making/data analysis • Release/secure mechanical interface • Remove module	• CRT did not respond to entry input at keyboard • Crew performed malfunction procedures • Problem isolated to stuck keyboard switch • Switch replaced from aft keyboard • Substituted switch cleared problem
STS-3 Orbiter Mission Report JSC 18348 June 1982	• Actuation of payload bay (16 mm) cameras Crew resets breaker and commands camera start and stop (STS-3)	• Activate/initiate system operation • Confirm/verify procedures/ • Sixth camera popped a circuit • Detect change in state or condition • Inspect/observe	• Five of six payload bay 16 mm movie cameras failed breaker • Breaker was reset • Camera failed to stop on command from crew • 90% of film run off before camera stopped

Table 2-2 Historical Precedents/Experiences as Observed in Previous Manned Mission Activities (Page 6 of 8)

DOCUMENT	MISSION ACTIVITY	INCLUDED GENERIC ACTIVITIES	COMMENTS
STS-3 Orbiter Mission Report JSC 18348 June 1982	• Closing of payload port door Actuator stalled during latch closure (STS-3)	• Activate/initiate system operation • Confirm/verify procedures/schedules • Detect change in state or condition • Implement procedures/schedule • Inspect/observe	• Actuator failed after approximately 23 hrs of orbiter in tail-sun attitude • Crew reorients to top-sun attitude • Crew recycles door • Door successfully closed and latched
STS-3 Orbiter Mission Report JSC 13348 June 1982	• Transmission of voice on wireless crew comm unit (STS-3)	• Activate/initiate system operation • Communicate information • Connect/disconnect electrical interface • Deactivate/terminate system condition • Detect change in state or condition • Gather/replace tools/equipment Implement procedures/schedule • Release/secure mechanical interface	• STS-3 CDR's unit failed to transmit • Unit would receive signal • Reported malfunction to ground control • Batteries replaced • Unit fails to transmit • Spare WCCU was deployed and communications were restored
SL-1 Operational Systems Debriefing December 1983	• General work performance in weightlessness (STS-9/SL-1)	• Information processing • Problem solving/decision making/data analysis	• STS-9/SL-1 • All crew activity during first "one or two days" was too heavy to do acclimatization to zero g • Due to need to acclimatize to zero g the first day or two should be planned as low work activity periods • Each crew member reported that it took between two and three days to really acclimatize to zero g
SL-1 Operational Systems Debriefing December 1983	• Hydrogen in drinking water (STS-9/SL)	• Detect change in state or condition • Implement procedures/schedules • Information processing • Problem solving/decision making/data analysis	• STS-9/SL-1 Near end of mission crew found hydrogen in drinking water • Crew improvised means of extracting hydrogen from water
SL-1 Operational Systems Debriefing December 1983	• Loud noises from structure in half hour t two hour intervals (STS-9/SL-1)	• Detect change in state or condition • Information processing • Inspect/observe • Problem solving/decision making/data analysis	• STS-9/SL-1 Crew observed loud noises • Estimated at 90 db level • Thought to be coinciding with hot/cold cases • Much energy involved
SL-1 Operational Systems Debriefing December 1983	• Minor difficulty in opening orbiter hatch (STS-9/SL-1)	• Detect change in state or condition • Release/secure mechanical interface • Remove/replace covering	• STS-9/SL-1 Hatch difficult to release • Residual spring tension in hatch mechanism • Possible (unconfirmed) delta P across hatch
SL-1 Operational Systems Debriefing December 1983	• Manual performance of orbital maneuvering (STS-9/SL-1)	• Activate/initiate system operation • Adjust/align elements • Communicate information • Confirm/verify procedures/schedules/operations • Deactivate/terminate system operation • Information processing • Problem solving/decision making/data analysis	• STS-9/SL-1 Performed 216 maneuvers on-orbit • 94 of 216 maneuvers were real time changes/additions • Tiring to orbiter crew • Recommend automatic maneuvering in future
SL-1 Operational Systems Debriefing December 1983	• Revision in procedures STS-9/SL-1	• Activate/initiate system operation • Communicate information • Confirm/verify procedures/ • Deactivate/terminate system operation	• STS-9/SL-1 • New and/or revised procedures not good practice • Cause of concern to crew

Table 2-2. Historical Precedents/Experiences as Observed in Previous Manned Mission Activities (Page 7 of 8)

DOCUMENT	MISSION ACTIVITY	INCLUDED GENERIC ACTIVITIES	COMMENTS
		• Implement procedures/schedules • Information processing • Inspect/observe	• Train and use in situ
SL-1 Operational Systems Debriefing December 1983	• Rework of fluid physics (column) experiment in real time (STS-9/SL-1)	• Activate/initiate system operation • Adjust/align elements • Communicate information • Deactivate/terminate system operation • Define procedures/schedules/operations • Detect change in state or condition • Implement procedures/schedules • Information processing • Inspect/observe • Problem solving/decision making/data analysis	• STS-9/SL-1 Fluid physics experiment did not go well, took longer than expected • Fluid column portion of experiment had difficulty • Crew interfaced with PI via T V to generate simple modifications • Experiment objective fulfilled
SL-1 Operational Systems Debriefing December 1983	• Waste Management System (WMS) Failure (STS-9/SL-1)	• Confirm/verify procedures/schedules/operations • Remove/replace covering • Replace/clean surface coatings	• STS-9/SL-1 Waste Management System (WMS) had problems by day 4, by day 7 was emitting human waste • Estimated that crew ate less to avoid using WMS
SL-1 Operational Systems Debriefing December 1983	• General scheduling of work STS-9/SL-1	• Allocate/assign/distribute • Define procedures/schedules/operations • Implement procedures/schedules • Inspect/observe	• STS-9/SL-1 Work scheduled 12 hr on, 12 hr off • SL-1 crew were happy with schedule and recommend no change • STS-9 crew commander suggests a third orbiter crewman also trained as a mission specialist (relief man for contingency)
Aviation Week & Space Technology December 19, 1983	• Blood samples required for STS-9/SL-1 life sciences investigations	• Gather/replace tools/equipment • Store/record element • Surgical manipulations	• STS-9/SL-1 • Blood drawn from two payload & mission specialists for life sciences investigations
Aviation Week & Space Technology December 19, 1983	• Experiment setup for measuring of pulsing of blood through body (STS-9/SL-1) • Ballistocardiography utilized accelerometers strapped to body Sensed body motion resulting from internal blood flow	• Plot data • Activate/initiate system operation • Apply/remove biomedical sensor • Confirm/verify procedures/schedules/operations • Deactivate/terminate system operation • Decode/encode data • Display data • Gather/replace tools/equipment • Store/record element	• STS-9/SL-1 • Internal blood flow life sciences experiment
Aviation Week & Space Technology December 19, 1983	• Failure of metric camera (German experiment) on (STS-9/SL-2) • Second cassette jammed on 25th frame of 400	• Activate/initiate system operation • Communicate information • Correlate data • Deactivate/terminate system operation • Gather/replace tools/equipment • Implement procedures/schedules • Inspect/observe • Precision manipulation of objects • Problem solving/decision making/data analysis • Release/secure mechanical interface • Remove/replace covering	• STS-9/SL-1 • Metric camera (German) and film cassette jammed • JSC ground linked to Zeiss camera in Germany and to STS-9/SL-1 crew • Repair procedures worked out in real time at JSC • JSC ground crew devised, fixed and walked flight crew through procedures to repair to jam • Relayed to crew to affect repair • Camera put back on line by flight crew
Aviation Week & Space Technology December 19, 1983	• Removal of malfunctioning isothermal furnace's electrical system from materials science rack to restore experiment to operational status on STS-9/SL-1	• Connect/disconnect electrical interface • Gather/replace tools/equipment • Inspect/observe • Problem solving/decision making/data analysis • Remove module • Remove/replace covering	• STS-9/SL-1 • Materials science rack problems - Stuck material sample - Vacuum leak - Electrical short

Table 2-2 Historical Precedents/Experiences as Observed in Previous Manned Mission Activities (Page 8 of 8)

DOCUMENT	MISSION ACTIVITY	INCLUDED GENERIC ACTIVITIES	COMMENTS
			• On board diagnostic checkout and electrical bypass (isolation) by crew saved majority of experiment
Aviation Week & Space Technology December 19, 1983	• Repair of high rate data recorder on STS-9/SL-1	• Activate/initiate system operation • Connect/disconnect electrical interface • Deactivate/terminate system operation • Inspect/observe • Precision manipulation of object • Remove/replace covering	• STS-9/SL-1 • High rate data recorder failed on 5th day • Recorder opened - 3 rollers found to be stuck • Rollers freed • System restored
Aviation Week & Space Technology December 19, 1983	• Revision of fluid physics module experiment on STS-9/SL-1	• Activate/initiate system operation • Allocate/assign/distribute • Communicate information • Connect/disconnect fluid interface • Deactivate/terminate system operations	• STS-9/SL-1 • Fluid physics module experiment had overflow problems • Ground personnel devised modifications • Flight crew applied fix
STS 41-C Flight Crew Report May 1984	• Requirement for crew to monitor and photograph the honeycomb structure created by Italian honeybees while in a weightless environment	• <u>Handle/inspect/examine living organisms</u> • <u>Measure (scale) physical dimension</u> • Activate/initiate system operation • Detect change in state or condition • Position module	• A series of photographs, TV recordings and two temperature measurements were made on three occasions • The crew found the experiment both interesting and entertaining
STS 41-C Flight Crew Report May 1984	• Requirement for on-orbit repairs of the Solar Maximum spacecraft	• <u>Transport unloaded</u> • Confirm/verify procedures/schedules/operations • Connect/disconnect electrical interface • Gather/replace tools/equipment • Position module • Release/secure mechanical interface • Remove module • Remove/replace covering • Transport loaded	• Positioning of the MFR was expeditious and enabled crewmember placement within fractions of an inch of the desired worksite • The MFR aided the replacement mission and it was found that maneuvering the 500 lb module was no problem • The EVA power tool worked very well and should be considered a standard tool
STS 41-C Flight Crew Report May 1984	• Utilization of MMU thruster cue lights during the docking and stabilization attempts	• <u>Compensatory tracking</u> • Information processing • Problem solving/decision making/data analysis	• MMU was flown with attitude hold • Thruster cue lights indicate when thrusters are automatically firing to maintain desired attitude

for any future manned system would be that the crewmen have equipment and suitable restraint and mobility aids to go anywhere on the interior or exterior of the vehicle while in orbit.

The presence of crewmen and the availability of manpower to correct problems and maintain equipment should result in a lower weight system overall. As an example, Skylab estimates (made after the failure of the orbital workshop solar wing to deploy automatically) indicated that a manual deployment mode for the solar arrays would have produced a 15 percent weight savings in that subsystem.

In both the Apollo Telescope Mount and the Earth Resources Experiment Package Payload on Skylab, the crewmen proved invaluable in assisting and directing the pointing capability of both these experiments. The crewmen greatly enhanced the quality of the data retrieved by being able to observe the overall situation and direct or point the experiment at the areas of interest. It is in this area of making selective executive decisions that man's role is irreplaceable.

On Skylab it was found that the space limitations that a man experiences here on Earth due to gravity did not necessarily apply in orbit. For example, the large food lockers (in excess of 6 cu ft and over 250 lb) were very readily relocated in zero gravity by one crewman working alone as compared to four men required on the ground.

In the debriefings, all crewmen agreed that zero gravity will in the future allow the designer of an orbital system more freedom in selecting volumes and weights for the crewmen to manipulate. One crewman made the statement that it would have been feasible in space to relocate an object the size of the film vault. (The Skylab vault was in excess of 12 cu ft and weighed approximatey 3,000 lb.)

Examples of these past experiences drawn from previous missions were valuable not only in confirming man's capability to perform specific activities in space but also in establishing a basis for developing a generic set of activities in Task 2 that could be used to describe future missions.

Section 3
SPECIFIC PROJECT ASSESSMENTS - TASK 2

The objective of Task 2 was to define and describe a structured approach for optimizing the role of humans and humans supported by machines in carrying out the requirements of selected space projects. To accomplish this objective, a generic list of activities was derived (Section 3.1) that could be used to describe any future space mission. This list of activities was compared to the human performance capabilities and limitations summarized in Task 1 to determine the degree of human involvement that can reasonably be expected to be associated with each of the individual activities. Past experience suggests that the utilization of the capabilities of the human element in the implementation of any man-machine system is limited only by the creative imagination of the system designer, with only a few exceptions. The principal limiting factor in the direct involvement of the human in system operation is the finite human response time associated with the performance of any activity or task. Accordingly, in Section 3.2 ranges of response times to be expected in the performance of each activity are presented for each of the man-machine modes, from direct manual involvement to indirect or independent systems operations. These timeline data were derived from many sources including prior system operations, research data, simulations and engineering analyses.

In Section 3.3, the supporting equipment and resources needed to implement each activity in each mode of man-machine interaction are identified. In Section 3.4, the economic factors and cost of equipment and other activities associated with providing, supporting, and utilizing human capabilities in advanced space missions are identified and quantified.

In Section 3.5, a method is presented for evaluating in qualitative and quantitative terms the cost effectiveness of varying degrees of human involvement in meeting the requirements of future space projects and missions.

3.1 SELECTED PROJECT ANALYSES

In order to derive a generic list of activities that could be used to describe any future space mission, various space projects were analyzed. The analyses entailed the definition of the various levels of events used to describe a given mission. It was recognized that each project could require one or more missions to be performed. In the cases examined each mission was broken down to the sequence level to describe the detailed operations for the given mission. As illustrated in Figure 3-1, the sequences were then further defined through the identification of the activities that made up each operational sequence. Once the activity level events were defined it was found that a great deal of commonality existed among the various operational sequences and the missions. In other words, the same basic activities were found to be required in different operations and in different missions. The activities were grouped together to eliminate redundancy. The objective was to develop a final list of basic or generic activities, each with unique characteristics, that when combined could be used to describe any future space missions.

Based on the level of detailed information currently available, the Space Platform missions were selected for the initial analysis of activities. The Space Platform (Figure 3-2) project was a conceptually designed free-flying

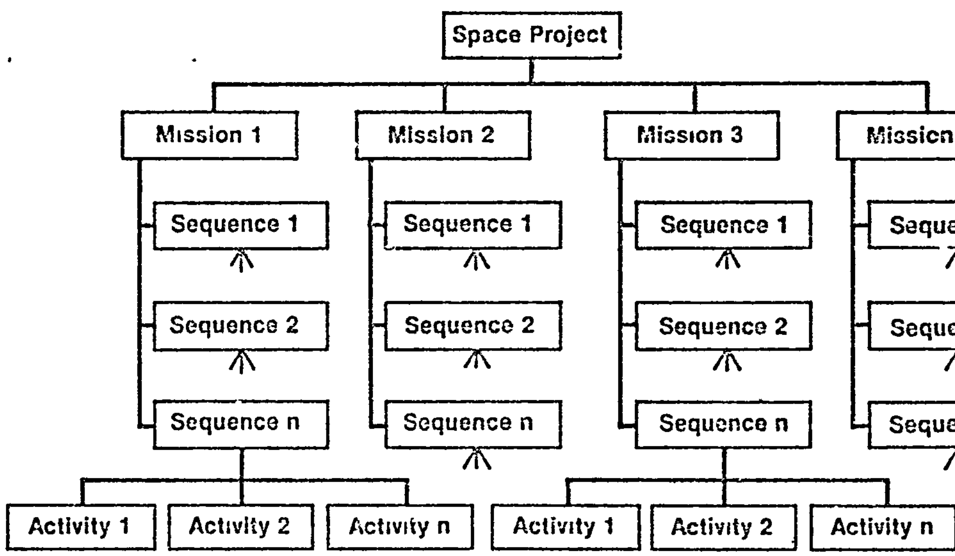


Figure 3-1. Project Analysis (Levels of Definition)

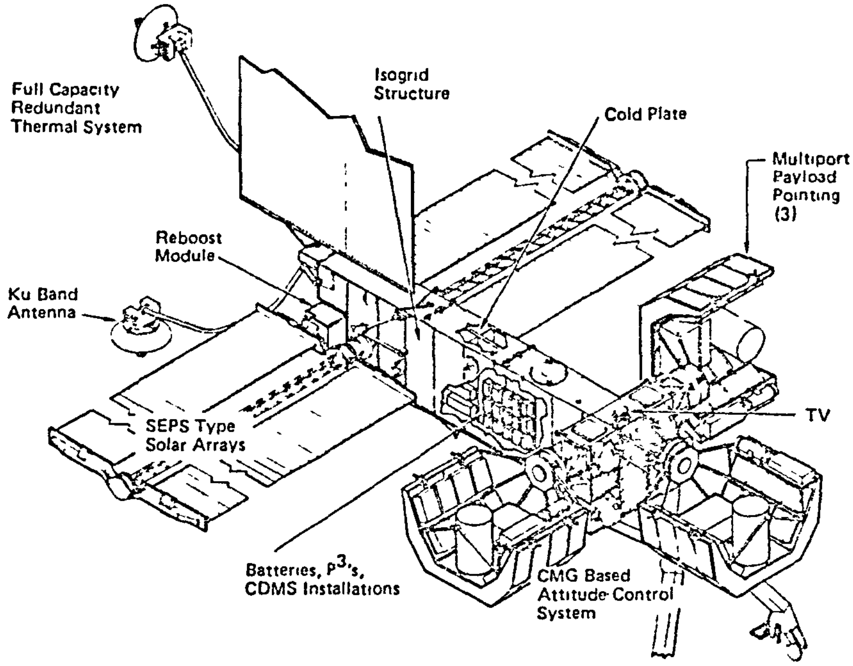


Figure 3-2. Space Platform System Design Concept

platform that could provide services such as electrical power, thermal control, and communications and data handling to a wide range of attached payloads. In scheduled revisits by the Space Shuttle, opportunities were provided for utilization of the human presence in maintenance, servicing, and repair as well as in the initial deployment and/or assembly of payloads. The source of information utilized in the analysis of the Space Platform missions was the MDAC Phase B Space Platform study reports (Reference 70). Based upon this information, the Space Platform missions were divided into their respective sequences and then the sequences were further categorized into the detailed operational activities. This analysis may be found in Appendix C-1.

The analysis of the Space Platform (Figure 3-3) resulted in the identification of five mission categories. Each of the respective missions was defined by the sequence level events required to perform those missions. As can be seen at the sequence level, several events may occur in more than one mission. For example, the berthing operation between the Space Platform and Space Shuttle not only appears in the payload reconfiguration mission as

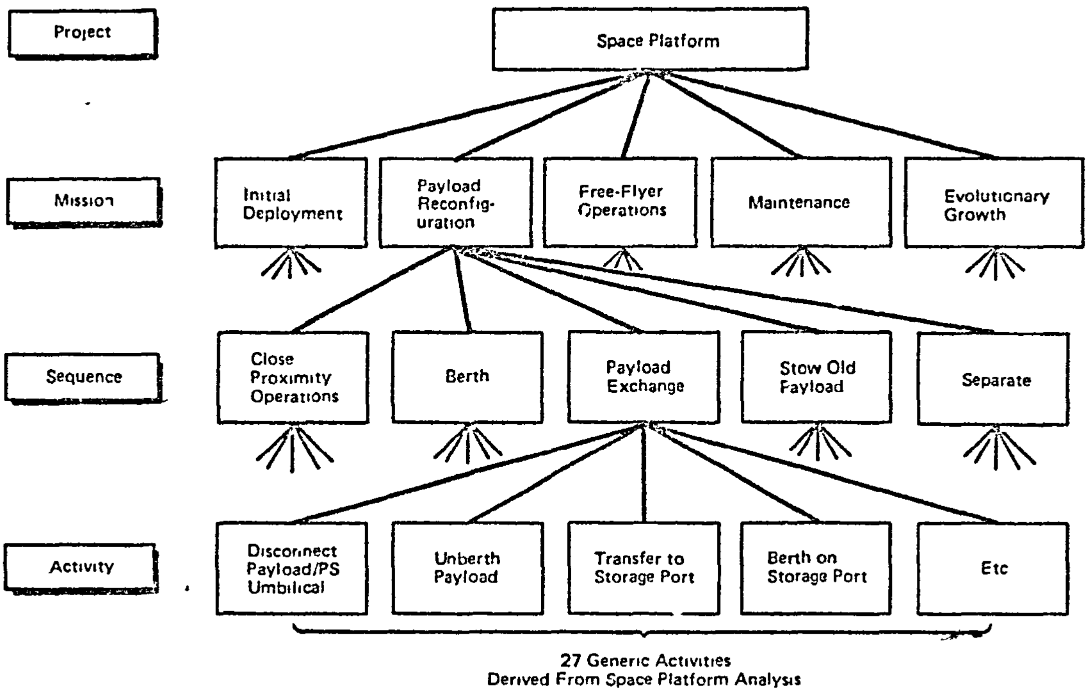


Figure 3-3. Space Platform Project Analysis

shown, but also in the initial deployment and maintenance missions, as well as evolutionary growth missions. The reason is that in order to perform those missions, it is required that the Space Platform and Space Shuttle be berthed together. The sequence level operations are then further defined by identifying the activities necessary to accomplish that operation. As stated previously, these identified activities were examined and combined where appropriate. On the basis of this analysis, 27 generic activities were derived.

The Generic Activity List continued to expand as other space projects were analyzed. The additional space projects that were examined included the Advanced X-ray Astrophysics Facility (AXAF) study; Skylab missions from SL-2, SL-3 and SL-4; Space Station mission models; and Life Sciences Laboratory missions. The analysis of the life sciences project (Figure 3-4) centered around three identified missions as shown in Figure 3-5. These missions were analyzed at the sequence level and each seqence in turn was redefined into its basic activities. An interesting note during this analysis was that even

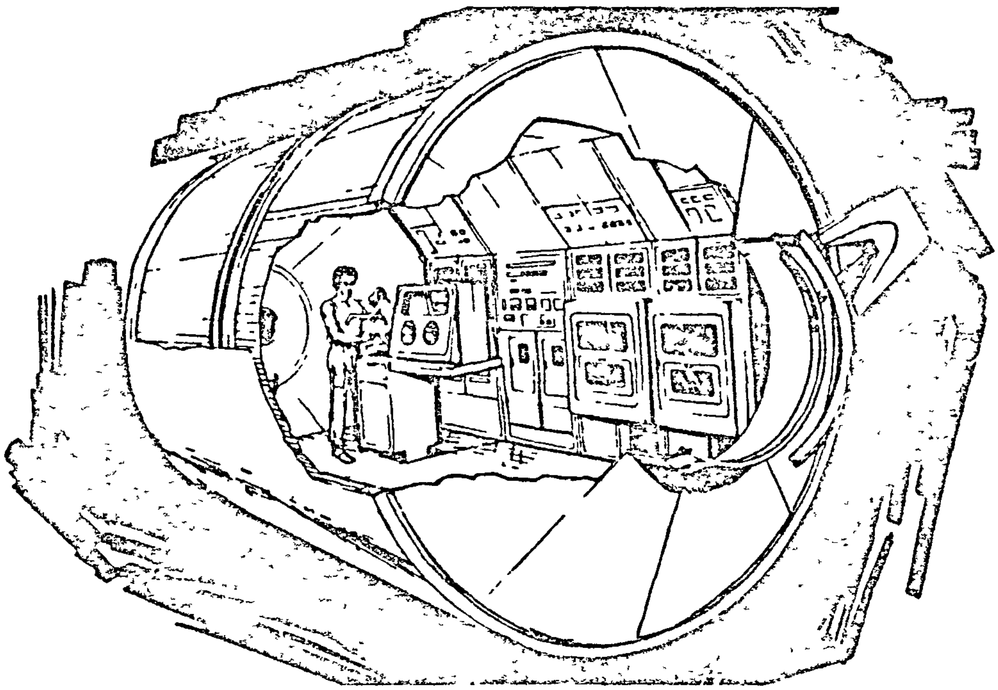


Figure 3-4. Life Sciences Dedicated Laboratory

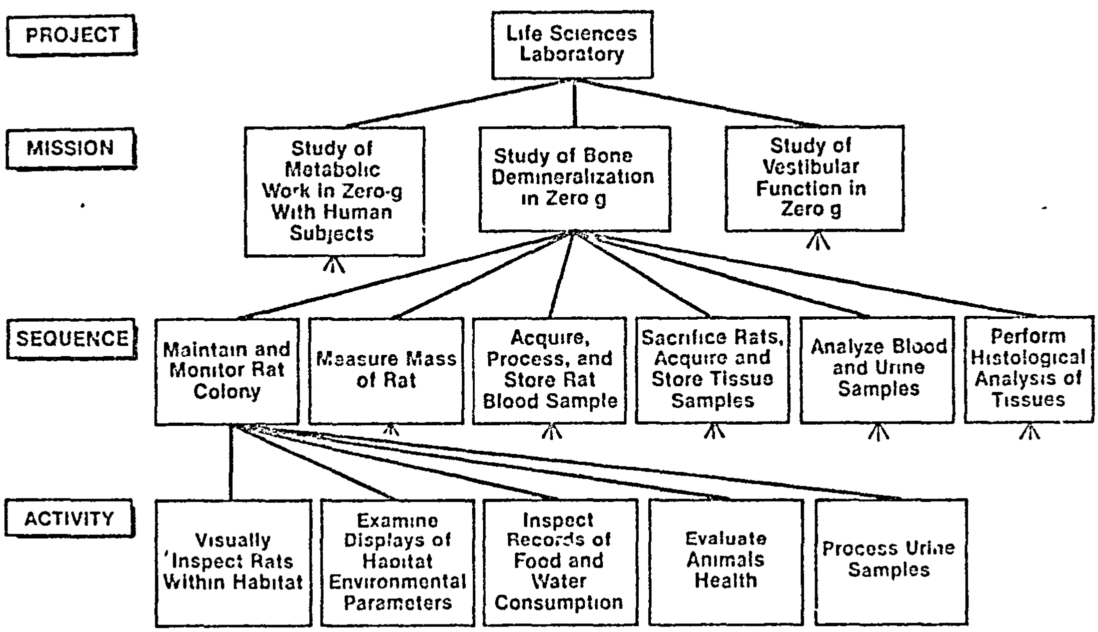


Figure 3-5. Life Sciences Laboratory (Project Analysis)

though the sequence level events were notably different for each life science mission there was once again considerable commonality among the activities required in the different mission elements. The analysis of the life sciences project may be found in Appendix C-2. Another information source which was utilized in these analyses was the MIT study of Automation, Robotics, and Machine Intelligence Systems (ARAMIS) study (References 67, 68, 69). This study had defined some 330 "Generic Functional Elements" and these functional elements were also matched against the listing of Generic Activities.

As each new source of mission data and/or mission activities was examined, the previously defined generic activities were matched against the new information. If a specific activity could not easily be described by one of the previously defined generic activities, a new activity category was identified for incorporation into the generic activity list.

The analyses of these space projects down to the activity level has resulted in the identification of the 37 unique activities. It is our belief that this set of generic activities will prove to be a useful tool in describing the operational sequences required in the broad spectrum of potential space missions anticipated in the coming decades.

Descriptions of each of the 37 Generic Activities follow:

1. Activate/Initiate System Operation. Those events and/or command sequences involved in the activation or initialization of a space based system or subsystem.

2. Adjust/Align Elements. Those adjustment activities involved in such operations as alignment of optical elements, fine tuning of precision electronic equipment, antenna pointing, and remote camera focusing operations.

3. Allocate/Assign/Distribute. Those activities involving the reallocation, or redistribution of resources: e.g., the redistribution of power, coolant flow, etc., to sensitive subsystem equipment to reflect operational needs or contingency operations.

4. Apply/Remove Biomedical Sensor. Those unique activities associated with the installation/removal and cleaning of sensors used to obtain biomedical data from a test subject.

5. Communicate Information. Those activities involving the establishment of the communications link and the transmission of information from one source

to another. It includes the verbal or visual interchange between two crewmen as well as the electronic transference of scientific information from a space probe to a terrestrial-based user.

6. Compensatory Tracking. Those activities involving continuous control adjustments to null an error signal against a fixed reference.

7. Compute Data. Those activities requiring a mechanized form of data processing such as in structural analyses, computation of positions of celestial bodies, or other forms of numerical computations.

8. Confirm/Verify Procedures/Schedules/Operations. Those activities involving the assessment of whether or not a prior event has in fact been accomplished (such as a system verification or checkout), or a procedure satisfied, or a schedule met.

9. Connect/Disconnect Electrical Interface. Those activities requiring the completion or termination of an electrical interface. They may involve utilization of blind-mated/self-aligning connectors, multiturn screw-drive interface plates, or similar devices.

10. Connect/Disconnect Fluid Interface. Those activities requiring the completion or termination of a fluid interface. They may involve utilization of a simple plug in, sleeve lock connection, multiturn screw drive interface plates, or similar devices.

11. Correlate Data. Those activities involving the identification of positive or negative relationships or commonalities among data sets such as organizational structures, characteristics, or processes.

12. Deactivate/Terminate System Operation. Those events and/or command sequences involved in the termination or deactivation of a space-based system or subsystem.

13. Decode/Encode Data. Those activities involving the conversion of data into either its original form or into a form compatible for transmission: e.g., converting transmitted digitized data into its original analog form or digitizing analog data for transmission to the ground station.

14. Define Procedures/Schedules/Operations. Those activities involving logical deductions or convergent production leading to development of procedures, schedules, or operations with predictable outcomes.

15. Deploy/Retract Appendage. Those activities associated with the extension of a hardware element to a position where its assigned function can be realized, or conversely, the stowing of that hardware element based on task completion or safety considerations.

16. Detect Change in State or Condition. Those activities where the departure of a parameter from its original or reference state or condition is required to be sensed or observed.

17. Display Data. Those activities involving the presentation of information/data by visual, auditory, or tactile means.

18. Gather/Replace Tools/Equipment. Those activities involved in the obtaining or in the returning of tools or equipment used to perform a specific task such as collecting or replacing maintenance tools or donning/doffing the Manned Maneuvering Unit (MMU).

19. Handle/Inspect/Examine Living Organisms. Those activities involving the unique operations associated with working with living organisms. These activities involve the manipulation and general handling of animals ranging from stroking to inspecting or examining anatomical characteristics.

20. Implement Procedures/Schedules. Those activities involving the instituting and carrying out of procedures or schedules (such as updating a mission model/schedule) as distinguished from activating or initiating system operations.

21. Information Processing. Those activities involving the categorizing, extracting, interpolating, itemizing, tabulating, or translating of information.

22. Inspect/Observe. Those activities involving the critical appraisal of events or objects. They may include the verification or the identification of a particular element such as damage inspection of a returning OTV, the observation and identification of a celestial object, or the behavior of a living organism.

23. Measure (Scale) Physical Dimensions. Those activities involving the estimation or appraisal of a dimension against a graduated standard or criterion.

24. Plot Data. Those activities involving the mapping, displaying, or locating of data by means of a specified coordinate system.

25. Position Module. Those activities involving the positioning of a component into a desired orientation: e.g., installing a new component, or tilting a payload into its launch orientation.

26. Precision Manipulation of Objects. Those activities involving tasks which require a high degree of manual dexterity in order to be accomplished such as the assembly/disassembly of small intricate mechanisms or the installation of measurement sensors, i.e., strain gauges, thermocouples, etc.

27. Problem Solving/Decision Making/Data Analysis. Those judgmental and sometimes creative activities involving the drawing of inferences or conclusions through the use of cognition, convergent or divergent production, memory, and comparative evaluation. Functions to be performed may include analyzing, calculating, choosing, comparing, estimating, or planning.

28. Pursuit Tracking. Those activities involving continuous control adjustment to match actual and desired signals when the desired or reference signal is continually changing.

29. Release/Secure Mechanical Interface. Those activities involving the manipulation of a mechanical interface ranging from a simple one-handed, over-center latch application to a high torque, multiturn threaded fastener. May involve manipulation of multiple fasteners arranged in various patterns or configurations.

30. Remove Module. Those activities involving the physical extraction or removal of a component after the mechanical, electrical, or thermal interfaces have been released or disconnected.

31. Remove/Replace Covering. Those activities involving the removal or reinstallation of an access covering or a protective covering as required to gain access to system elements or to cover them up upon completion of the work.

32. Replace/Clean Surface Coatings. Those unique activities involving the restoration of a degraded/contaminated surface coating such as replacing a radiator's thermal coating or cleaning an optical systems viewing surface.

33. Replenish Materials. Those activities involving the resupplying of consumables such as refueling a spacecraft, recharging an optics cryo-based cooling system, or providing food supplies to an animal holding facility.

34. Store/Record Element. Those activities involving the recording or storage of items for both short-term and long-term periods: e.g., recording/storage of experimental data or temporary storage of a biomedical sample.

35. Surgical Manipulations. Those activities, such as a surgical procedure or a dissection including tissue sample acquisitions, that require a high degree of skill and knowledge as well as manual dexterity in order to be accomplished.

36. Transport Loaded. Those activities involving the conveying of a physical object by some transportation device from one location to another: e.g., the transporting of a component via a crewman or a remote manipulator system.

37. Transport Unloaded. Those activities involving the movements of an unloaded individual or device from one location to another: e.g., the movement of a crewman to a worksite without carrying tools or equipment, or the movement of a remote manipulator system with nothing attached.

Figure 3-6 identifies the sources from which each of the generic space activities that compose the final listing was derived.

3.2 MISSION TIMELINES

Once a generic set of activities had been established that could be used to describe any future space mission, the next step was to establish the relative applicability and value of the alternative man-machine modes in accomplishing these activities, both individually and in composite as might be dictated by a specific set of mission requirements. In order to establish the degree of human involvement that could reasonably be expected to be associated with each of the individual activities, three sets of performance criteria were considered: the first set was the range of performance times required to accomplish the task; the second set was the requirements for human involvement in terms of sensory/perceptual, intellectual and psychomotor functions; and the third set was the limiting factors in human involvement in terms of the human response capabilities for sensing, information processing, and motor actions.

In addressing the criterion of performance time requirements, mission timeline data available from prior space missions, laboratory studies, system simulations and engineering design studies were utilized to establish a reference set of timeline data for each activity and for each category of man-machine interaction.

The categories of man-machine interaction are based upon the human operator's level of participation in the performance of the task and were defined as follows:

Manual. Unaided IVA/EVA, with simple (unpowered) hand tools

Supported. Use of supporting machinery or facilities required to accomplish assigned tasks (e.g., manned maneuvering units, foot restraint devices, etc.)

Generic Space Activities	Source					
	AXAF	(1) Skylab	(2) Space Platform	Space Station	(3) ARAMIS Study (MIT)	Life Sciences Laboratory
1 Activate Initiate System Operation	●	●	●	●	●	●
2 Adjust/Align Elements		●		●	●	●
3 Allocate/Assign/Distribute		●	●	●	●	●
4 Apply/Remove Biomedical Sensor		●		●	●	●
5 Communicate Information	●	●	●	●	●	●
6 Compensatory Tracking				●	●	
7 Compute Data	●	●	●	●	●	●
8 Confirm/Verify Procedures/Schedules/Operations		●	●	●	●	●
9 Connect/Disconnect Electrical Interface		●	●	●	●	●
10 Connect/Disconnect Fluid Interface		●	●	●	●	
11 Correlate Data		●	●	●	●	●
12 Deactivate/Terminate System Operation	●	●	●	●	●	●
13 Decode/Encode Data			●	●	●	
14 Define Procedures/Schedules/Operations		●	●	●	●	●
15 Deploy/Retract Appendage	●	●	●	●	●	
16 Detect Change in State or Condition		●		●	●	●
17 Display Data		●	●	●	●	●
18 Gather/Replace Tools/Equipment	●	●	●	●	●	●
19 Handle/Inspect/Examine Living Organisms						●
20 Implement Procedures/Schedules		●	●	●	●	●
21 Information Processing		●		●	●	●
22 Inspect/Observe		●	●	●	●	●
23 Measure (Scale) Physical Dimensions		●			●	
24 Plot Data		●	●	●		●
25 Position Module	●	●	●	●	●	●
26 Precision Manipulation of Objects		●		●		
27 Problem Solving/Decision Making/ Data Analysis		●	●	●	●	●
28 Pursuit Tracking		●	●	●	●	
29 Release Secure Mechanical Interface	●	●	●	●	●	●
30 Remove Module	●	●	●	●	●	●
31 Remove/Replace Covering		●	●		●	●
32 Replace Clean Surface Coatings	●		●			●
33 Replenish Materials	●	●		●	●	●
34 Store/Record Elements		●	●	●	●	●
35 Surgical Manipulations						●
36 Transport Loaded	●	●	●	●	●	●
37 Transport Unloaded	●	●	●	●	●	

(1) Includes EREP and ATM Activities

(2) Includes Activities Derived from the Analysis of Space Platform Ground System Data Management Study

(3) Includes 330 Generic Functional Elements Derived from the Geosynchronous Platform Advanced X Ray Astrophysics Facility Teleoperator Maneuvering System and Space Platform

Figure 3 6 List of Generic Activities

Augmented. Amplification of human sensory or motor capabilities (powered tools, exoskeletons, electron microscopes, etc.)

Teleoperated. Use of remotely controlled sensors and actuators allowing the human presence to be removed from the work site (remote manipulator systems, teleoperators, telefactors)

Supervised. Replacement of direct manual control of system operation with computer-directed functions although maintaining humans in supervisory control from ground-based or orbital-based work stations

Independent. Basically independent self-actuating, self-healing operations but requiring human intervention occasionally (relies heavily on automation and artificial intelligence)

Summary timeline profiles, as shown in Figure 3-7, were prepared for each of the 37 activities to depict the range of times associated with each mode of man-machine interaction. The timeline profiles for each of the 37 activities may be found in Appendix D. In each case, the timeline profiles were constructed in accordance with the following groundrules:

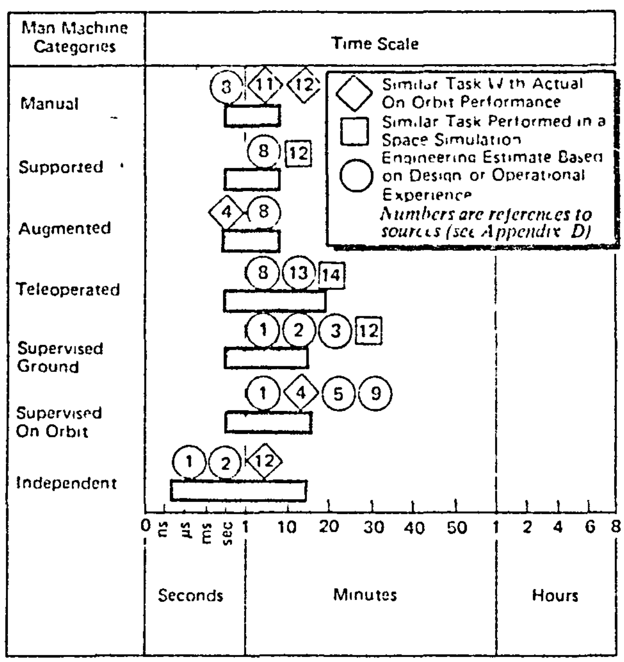


Figure 3-7. Typical Activity Timeline Profile Activate/Initiate System Operation

- All of the generic space activities encompass events that will be performed on-orbit.
- The range of time for accomplishing a task is defined by a minimum task time and a maximum task time based on specific tasks identified during the analysis of previous space projects (references cited).
- The times are based either on actual space performance (◇), a space simulation (□), or on engineering estimates derived from conceptual designs or from similar operational experiences (○). (The numbers within the symbols designate the specific data sources. These sources are listed in Appendix D.)
- Those activities that were determined to require direct human involvement for accomplishment will not be considered for supervised or independent applications.
- Operations in the manual category will be limited to 50 minutes based on evaluations associated with manual fatigue levels and span-of-attention limits.
- For activities that require support equipment, it is assumed that the crewmen have a working/operational knowledge of that equipment and special training is not required.

An important consideration when evaluating manual task performances is whether or not times differ for accomplishing similar tasks in the EVA as compared to the IVA mode of operation.

In order to provide a basis for estimating the times for accomplishing activities in each of these modes, comparative data were needed on fine and coarse motor activities to be performed in zero g both with and without a pressurized suit. Since such data was not readily available from actual space flights, we elected to develop these data by analyzing video tapes taken in the MDAC and the MSFC Neutral Buoyancy Simulators during the past year. In 1983, MDAC performed two series of Neutral Buoyancy Tests in which the same maintenance and servicing tasks were performed. The first test was performed in SCUBA only, which equates to the simulated IVA environment. The second test series involved pressure-suited subjects, which simulated the EVA environment. By comparing task performance times for a representative selection of tasks requiring fine and coarse motor activities under simulated zero g (neutral buoyancy) when using a pressure unit and when using scuba

equipment only, it was believed a reasonable basis of relating IVA and EVA task times could be obtained. It was hypothesized that the scuba performance would be equivalent to an IVA performance in zero g.

As an example of coarse mo r movements, a handcranking operation such as might be involved in deploying an appendage was selected. Observational data were available from the video tapes for three crank radii (3 inches, 6 inches, and 9 inches) for a series of scuba and pressure suit trials.

In similar fashion, observational data related to fine motor movements were available under each condition for two tasks: (1) mating and demating electrical connectors, and (2) removing and installing fluid interfaces.

Figure 3-8 plots the average times observed (Table 3-1) under each operational mode for the various crank radii. Table 3-2 summarizes the average times observed for the tasks requiring fine motor movements.

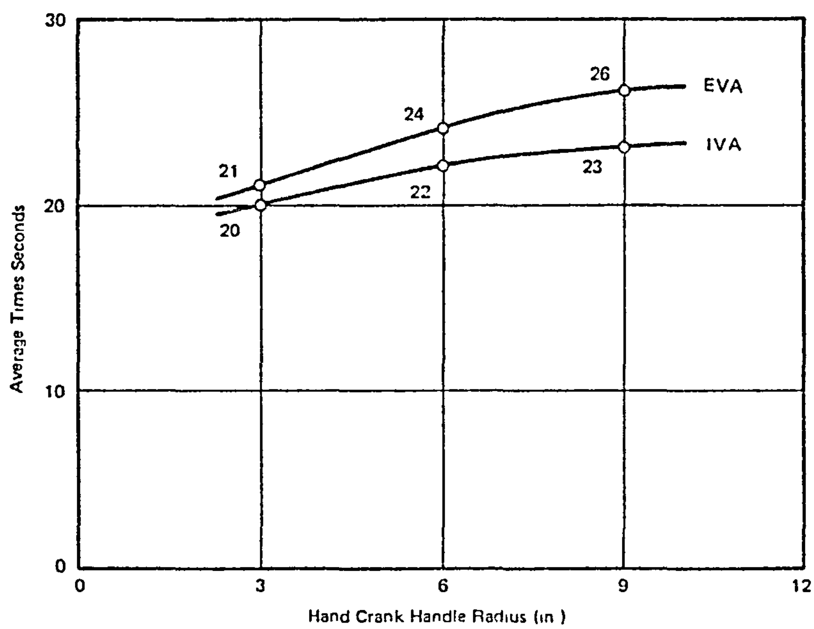


Figure 3-8. Coarse Motor Movements

Table 3-1. IVA and EVA Task Time Comparisons
(Coarse-Motor Movements)

Task	Average times (sec) IVA	EVA	Ratio EVA/IVA
Manual hand crank			
3-inch radius	20	21	1 05
6-inch radius	22	24	1 09
9-inch radius	23	26	1 13
Average			1 09

From this observational data, it was concluded that the times for performing coarse motor movements should be roughly comparable for most IVA and EVA operations (Table 3-1), although as may be noted in Figure 3-8, the greater the movement required (as in the case of turning a crank with a nine inch radius), the greater the discrepancy becomes between the IVA and EVA performance times. The differences observed are undoubtedly due to the restrictions in pressure suit articulation. In the case of fine motor movements, (Table 3-2) the EVA operations seem to take about 1.5 times longer. This difference can be attributed to the sensitivity and dexterity differences between the gloved versus the ungloved hand.

Table 3-2 IVA and EVA Task Time Comparisons
(Fine-Motor Movements)

Task	Average times (sec) IVA	EVA	Ratio EVA IVA
Electrical connectors			
Coax – 6 turns, threaded	19	31	1 63
Bayonet – 120-deg lock and unlock	9	14	1 75
Fluid interface			
Remove	10	13	1 30
Install	14	20	1 14
Average			1 53

It is believed that the timeline data derived from the neutral buoyancy chambers is a very reasonable approximation of the actual times that will be experienced in zero g. To substantiate this hypothesis, the Skylab EVA tasks were reviewed by the study team. Table 3-3 compares the planned times based on neutral buoyancy simulations on the ground and the actual times observed in space for ten composite EVA tasks on Skylab 2, 3, and 4 for which data were

Table 3-3. Skylab EVA Tasks

EVA events	Planned time (minutes)	Actual timr (minutes)	Δ time (minutes)
1	45	35	-10
2	248	203	-45
3	105	96	-9
4	448	391	-57
5	275	270	-5
6	156	161	+5
7	388	394	+6
8	442	413	-29
9	212	209	-3
10	323	319	-4
Total	2642	2491	-151
Overall – 6% under estimate (151/2642 minutes)			

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available. Out of a total of 2642 minutes of planned operations, the actual EVA times totaled 2491 minutes or 6% less (faster) than had been allocated. Based on this prior experience, it was concluded that the time estimates derived from the recently conducted neutral buoyancy simulations provide reasonable estimates of on-orbit performance times, at least to the level of precision required for the THURIS study.

In view of the data suggesting: (1) the general compatibility of IVA and EVA performance times; (2) the validity of neutral buoyancy data as a basis for estimating performance times in zero gravity; and (3) the high probability that an 8-psi EVA suit requiring no prebreathing time will be available in time for missions now in the conceptual design stage; it was concluded that no differentiation would be required between IVA and EVA for the purposes of a first approximation of performance times. The design decision as to whether EVA or IVA would be required in future systems will be established by programmatic criteria other than performance times. Accordingly, the timeline profiles appearing in Appendix D do not differentiate between the IVA and the EVA modes for the manual, supported, and augmented categories.

In addition to performance times, the other criteria considered in defining the applicability of the various modes of man-machine interaction were (1) the requirements for human involvement in terms of sensory/perceptual, intellectual, and psychomotor functions, and (2) the limiting factors in human involvement in terms of the human response

capabilities for sensing, information processing, and motor actions. The human capability data developed in Task 1, and described in Appendix A, provided the information used in this definition process. Figure 3-9 summarizes in matrix form the human capabilities defined in Section 2 that are required to perform each of the generic space activities.

An attempt was also made to identify the role that each of these capabilities played in each of the generic space activities; and, by assessing the importance of this role, to gain some understanding of the benefit of man's onboard participation in each activity. In some instances, the generic space activity could be applied to a broad range of mission activities, some of which would benefit significantly from man's participation and ~~others~~ of which would benefit very little or not at all. For most, however, a reasonably precise evaluation could be made. Table 3-4 presents the results of this assessment of the benefit of man's participation in each of the space activities.

The activity timeline profiles found in Appendix D also indicate the requirements for human involvement as well as the limiting factors in human involvement for each of the man-machine categories. The limiting factors noted on these timeline profiles reflect the human capability classifications that could be exceeded by the requirements of the specific activity. In these cases, additional support would be required from the machine elements in terms of enhancing the sensing, information processing, or motor actions of the human operator. Where limiting factors are exceeded, a transition into a more mechanized man-machine category will generally be required in order to obtain the optimal task performance considerations.

As an example of the issues considered at this point in the analysis, Figure 3-10 presents the timeline profile and notes the human capabilities required and the limiting factors associated with the various man-machine categories for the activity titled "Release/Secure Mechanical Interface". The ranges of times for accomplishing the activity have been determined from specific applications. Activities in the manual category for example could involve tasks ranging from simple, one-handed over-center latches to numerous multiturn captive fasteners that could be arranged in various patterns (see

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HUMAN CAPABILITIES / GENERIC SPACE ACTIVITIES	SENSORY/PER...									
	Visual Acuity	Detection and Discrimination of Brightness	Color Discrimination	Depth Perception and Discrimination	Peripheral Visual Detection and Discrimination	Visual Accommodation	Detection and Discrimination on Tone	Discrimination of Sound Intensity	Localization of Sound	Detection of Light Touch
	1	2	3	4	5	6	7	8	9	10
1 Activate/Initiate System Operation	●		●							
2 Adjust/Align Elements	●			●		●				
3 Allocate/Assign/Distribute										
4 Apply/Remove Biomedical Sensor	●									●
5 Communicate Information	●	●	●							
6 Compensatory Tracking	●									
7 Compute Data	●					●				
8 Confirm/Verify Procedures/Schedules	●									
9 Connect/Disconnect Electrical Interface	●					●				●
10 Connect/Disconnect Fluid Interface	●					●				●
11 Correlate Data										
12 Deactivate/Terminate System Operation	●									
13 Decode/Encode Data	●									
14 Define Procedures/Schedules/Operations										
15 Deploy/Retract Appendage	●									
16 Detect Change in State or Condition	●	●	●			●	●	●	●	●
17 Display Data	●									
18 Gather/Replace Tools/Equipment	●									
19 Handle/Inspect/Examine Living Organisms	●					●				●
20 Implement Procedures/Schedules										
21 Information Processing	●	●	●				●	●	●	
22 Inspect/Observe	●	●	●	●		●				
23 Measure (Scale) Physical Dimensions	●			●						
24 Plot Data	●									
25 Position Module	●					●				●
26 Precision Manipulation of Objects	●			●		●				
27 Problem Solving/Decision Making/ Data Analysis	●	●	●			●	●	●	●	
28 Pursuit Tracking	●									
29 Release/Secure Mechanical Interface	●					●				●
30 Remove Module	●					●				●
31 Remove/Replace Covering	●									
32 Replace/Clean Surface Coatings	●		●			●				
33 Replenish Materials	●									
34 Store/Record Element	●									
35 Surgical Manipulations	●		●	●		●				
36 Transport Loaded	●			●						
37 Transport Unloaded	●			●						

SENSORY/PERCEPTUAL													INTELLECTUAL				PSYCHOMOTOR				MOTOR	
Visual Accommodation 6	Detection and Discrimination on Tone 7	Discrimination of Sound Intensity 8	Localization of Sound 9	Detection of Light Touch 10	Tactile Recognition of Shape and Texture 11	Discrimination of Force Against Limb 12	Recognition of Limb (Movement and Location) 13	Detection and Discrimination of Angular Acceleration 14	Equilibrium 15	Detection and Discrimination of Vibration 16	Detection of Heat and Cold 17	Detection and Discrimination of Odors 18	Cognition 19	Memory 20	Divergent and Convergent Production 21	Evaluation 22	Production and Application of Force 23	Control of Speed of Motion 24	Control of Voluntary Responses 25	Continuous Adjustment Control (Tracking) 26	Arm/Hand/Finger Manipulation 27	Body Positioning 28
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						●	●		●				●			●	●		●	●	●	●

Figure 3-9 Human Capabilities Required for Each Activity

Table 3-4. Benefit of Man's Participation in Space Activities (Page 1 of 2)

No	Generic space activity	Key capabilities utilized in man's participation	Benefit of man's onboard participation: Equipment can be eliminated	Performance of activity is improved	Probability of mission success is increased	Overall benefit from man's onboard participation	Rationale
1	Activate initiate system operation	Evaluation Vision Manipulation	Minimal	In some cases	Negligible	Not significant	Automatically activated systems will predominate
2	Adjust align elements	Vision Cognition Evaluation	Yes	In some cases	No	Beneficial	Most alignment operations within man's capabilities
3	Allocate assign distribute	Cognition Convergent Prod	No	In some cases	Minimal	Not significant	Primarily automated operations
4	Apply remove biomedical sensors	Cognition Manipulation	Not applicable	Yes	Yes	Essential	Operations cannot easily be automated
5	Communicate information	Cognition Vision	No	In some cases	No	Not significant	Communication link established automatically
6	Compensatory tracking	Cognition Evaluation Vision Manipulation	Minimal	No	Minimal	Not significant	Highly dependent on nature of tracking task Nullifying error signal could be automatic
7	Compute data	Cognition Evaluation	No	No	Minimal	Not significant	Man will play negligible role in most data computation
8	Confirm verify procedures schedules operations	Cognition Evaluation	No	No	Minimal	Not significant	Man would usually function in a backup role only
9	Connect/disconnect electrical interfaces	Vision Gross Motor Act Manipulation Evaluation	Yes	Yes	Yes	Beneficial to essential	Typical utilization of man's basic capabilities
10	Connect/disconnect fluid interfaces	Vision Gross Motor Act Manipulation Evaluation	Yes	Yes	Yes	Beneficial to essential	Typical utilization of man's basic capabilities
11	Correlate data	Cognition Evaluation	No	In some cases	Minimal	Not significant	Man would usually function in a backup role only
12	Deactivate terminate system operation	Manipulation Vision Evaluation	Minimal	In some cases	Negligible	Not significant	Automatically deactivated systems will be the norm
13	Decode encode data	Cognition Convergent Prod	No	No	No	Not significant	Computer function only
14	Define procedures/ schedules operations	Cognition Divergent Prod.	Yes	Yes	Yes	Essential	Activity is wholly dependent on man's intellectual capabilities
15	Deploy retract appendage	Vision Gross Motor Act	Yes	In some cases	In some cases	Beneficial	Seldom repeated activities are poor candidates for automation
16	Detect change in state or condition	Cognition Evaluation Vision	No	In some cases	In some cases	Beneficial or essential	Strongly dependent on characteristics of activity
17	Display data	Cognition Evaluation	No	Yes	Yes	Beneficial to essential	[illegible] important in selection of data to be displayed
18	Gather/replace tools/ equipment	Cognition	Yes	Yes	Minimal	Beneficial to essential	Man can vary tool selection with respect to task
19	Handle inspect/ examine living organisms	Cognition Vision Manipulation	Not applicable	Yes	Yes	Essential	Activity cannot be automated in most cases
20	Implement procedures/schedules	Cognition Evaluation Convergent Prod.	Not applicable	Yes	Yes	Essential	Activity dependent on man's involvement by [illegible]
21	Information processing	Cognition Evaluation	Minimal	Yes	Yes	Beneficial to essential	Essential interaction between man and computer

Table 3-4. Benefit of Man's Participation in Space Activities (Page 2 of 2)

No	Generic space activity	Key capabilities utilized in man's participation	Benefit of man's onboard participation: Equipment can be eliminated	Performance of activity is improved	Probability of mission success is increased	Overall benefit from man's onboard participation	Rationale
22	Inspect observe	Vision Cognition Evaluation Divergent Prod.	Yes	Yes	Yes	Highly beneficial	Man's selective observations superior to automated monitoring
23	Measure (scale) physical dimensions	Vision Evaluation	In some cases	No	In some cases	Beneficial (in some cases	Man is best alternative in some situations
24	Plot data	Cognition	No	Minimal	No	Not significant	Primarily a computer function
25	Position module	Vision Evaluation Gross Motor Act	In some cases	In some cases	In some cases	Beneficial for some activities	Man's benefit highly dependent on type of activity
26	Precision manipulation of objects	Vision Manipulation Cognition	Yes	Yes	Yes	Most often essential	Man's manipulative skills cannot be duplicated by automatic devices
27	Problem solving/ decision making data analysis	Cognition Divergent Prod. Convergent Prod. Evaluation	Yes	Yes	Yes	Essential	Man essential by definition
28	Pursuit tracking	Cognition Manipulation	Minimal	Yes	Minimal	Could be significant	Dependent on specific tracking task
29	Release secure mechanical interface	Vision Gross Motor Act. Manipulation Evaluation	Yes	Yes	Yes	Beneficial to essential	Exemplary utilization of man's capabilities in space activity
30	Remove module	Vision Evaluation Gross Motor Act	In some cases	In some cases	In some case	Beneficial for some mission activities	Man's benefit highly dependent on type of activity
31	Remove replace covering	Vision Evaluation Gross Motor Act	In some cases	In some cases	In some cases	Beneficial for some cover removal replacement activities	Man's benefit highly dependent on task characteristics
32	Replace clean surface coatings	Vision Evaluation Gross Motor Act	Yes	Yes	Yes	Beneficial to essential	Infrequency of activity negates automation
33	Replenish materials	Vision Evaluation Gross Motor Act	Yes	In some cases	Yes	Beneficial to essential	Degree of benefit is dependent on nature of task
34	Store record element	Cognition	No	No	No	Not significant	Man's participation of benefit only in isolated cases
35	Surgical manipulations	Vision Manipulation Cognition	Not applicable	Yes	Yes	Essential	Activity not appropriate for automation
36 37	Transport loaded or unloaded	Vision Cognition Gross Motor Act	In some cases	In some cases	In some cases	Dependent on characteristics of task	Characteristics of tasks can vary extensively for this activity

Shaded activities are those where direct human participation is considered most beneficial or essential

Figure 3-11). Activities such as these require primarily sensory/perceptual and psychomotor capabilities in order to accomplish the assigned task. The physical action for accomplishing the task is the limiting factor since exerting high torques could be required. In the "Supported" man-machine category a crewman in restraints might perform the task with a manual ratchet

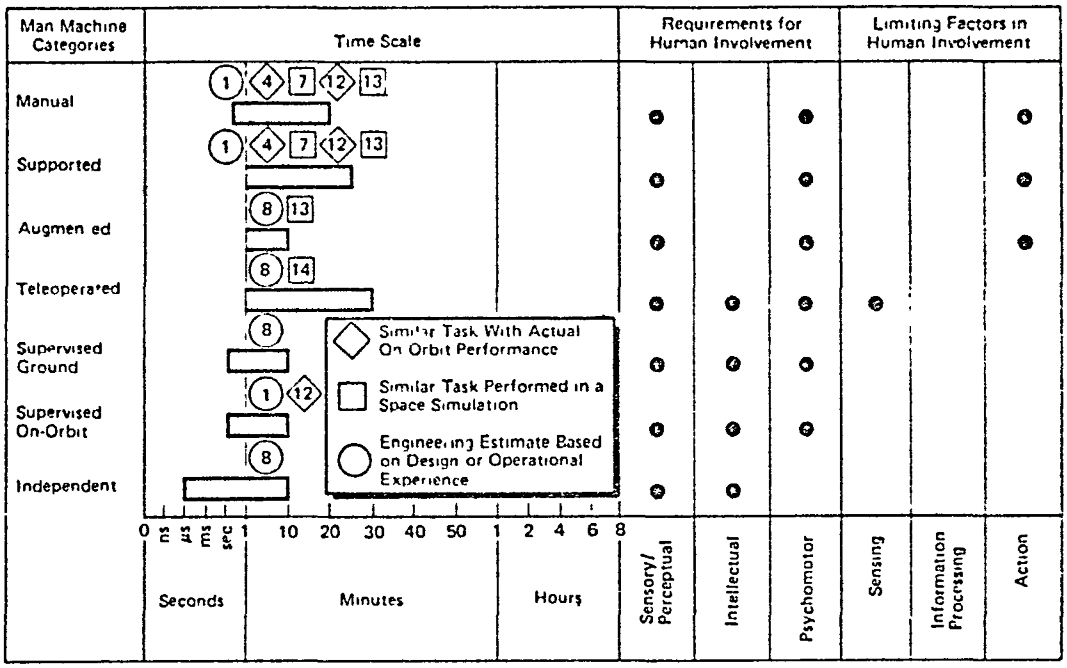
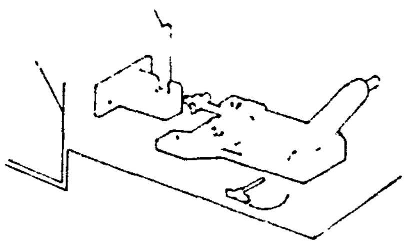


Figure 3-10. Release/Secure Mechanical Interface

wrench. However, if the force required to manipulate the mechanical interface requires more torque than the crewman can exert, then the action classification for that category is a limiting factor. In this case the activity would require augmentation in the form of a powered hand tool. Examples of tasks that might fall in the "Supervised" category involve commanding and monitoring mechanized mechanical interface activations such as the shuttle payload retention latches or launch restraint devices (see Figure 3-11). The on-orbit supervised category requires sensory/perceptual as well as intellectual capabilities on the human's part even though the action itself might be accomplished by remote control.

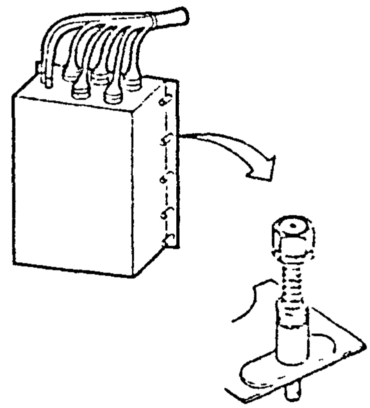
3.3 HUMAN SUPPORT REQUIREMENTS

Once the capabilities and limitations of each man-machine mode have been established and their impact on the performance of each activity identified, the next issue to be addressed is to determine the relative cost of each of the applicable modes of implementation. Assuming that two or more alternative implementation concepts will be feasible for accomplishing a specific



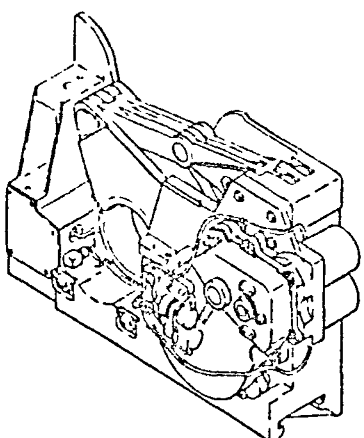
Manual

Simple, One Handed Over Center Latch Application



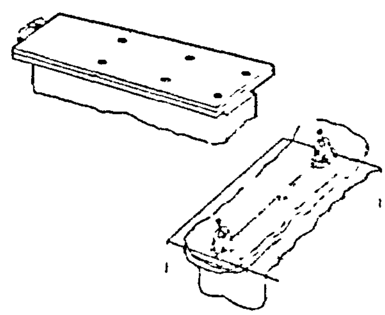
Manual

Multiturn, Numerous Captive Fasteners



Supervised

Command Activation of Shuttle Payload Retention Latch



Supervised

Command and Monitor Release of Launch Restraint Devices

Figure 3-11 Release/Secure Mechanical Interface Examples

activity, the determining factor in the mind of the system engineer becomes the question of cost. Accordingly, the resources and support equipment needed to accomplish each activity in each of the feasible man-machine modes was identified to a sufficient depth to allow comparative cost data to be developed.

The initial compilation of the resources and the support equipment was derived in conjunction with the timeline analyses described in Section 3.2. In addition, several past and ongoing space projects such as the Skylab missions and the Unmanned Space Platform missions were reviewed to ensure that the final listing of resource needs and support equipment represented all of the most pertinent items.

The support equipment necessary for the various man-machine modes included Facilities; EVA Support Items; Tool Kits and Mechanical Support Equipment; Command, Control, Communication, and Data Management Equipment; Orbital Mobility Systems; and Operating Systems Software. Table 3-5 lists the specific support equipment items identified in each of these categories. For reference purposes the paragraph numbers in Section 3.4 of this report that contain the costing information pertinent for each item in Table 3-5 are noted parenthetically on the table.

To provide a basis for estimating the relative costs of alternative man-machine modes, a specific operational example was selected for each activity. The example chosen was one for which a design concept was already available or one that in fact had been implemented in a previous program. This same example was then used for each of the man-machine modes that was applicable to the performance of a specific activity. For comparative purposes, this provided a common base for identifying the support requirements and for assessing the relative level of support necessary for each man-machine mode. Since the objective was only to determine the relative cost of implementing each mode, the use of a common example was believed to be adequate to provide a meaningful basis for comparison. While either simpler or more complex examples than those chosen would change the absolute magnitude of the support requirements and their associated costs, it was reasoned that the relative costs of the alternative man-machine categories would remain

Table 3-5

SUPPORT EQUIPMENT LIST FOR COSTING VARIOUS MAN-MACHINE MODES

A.	Facilities	
A1.	Space Station Facility	(3.4.1)
A2.	Ground Control Center, Baseline System	(3.4.2)
A3.	Payload Control Center, Baseline System	(3.4.2)
A4.	Data Handling Facility, Baseline System	(3.4.2)
A5.	Tracking and Data Relay Satellite System (TDRSS)	(3.4.3)
A6.	Unmanned Platform Basic Resources	(3.4.7)
B.	EVA Support Items	(3.4.4)
B1.	Extravehicular Mobility Unit (EMU)	
B2.	Manned Maneuvering Unit (MMU)	
B3.	Remote Manipulator System (RMS)	
C.	Tool Kits and Mechanical Support Equipment	(3.4.5)
C1.	Power Tool, Portable	
C2.	Tool Kits, Manual	
C3.	Gas Recharge Kit	
C4.	Fluid Recharge Kit	
C5.	Test Set, Alignment/Calibration, Portable	
C6.	Test Set, Electrical Checkout	
C7.	Surface Coating/Refurbishment Apparatus	
C8.	Support Equipment, Experiment Specific - Category A	
C9.	Support Equipment, Experiment Specific - Category B	
C10.	Support Equipment, Experiment Specific - Category C	
C11.	Support Equipment, Experiment Specific - Category D	
C12.	Cherry Picker with Work Platform (RMS)	
C13.	Restraints to Support Manned Activities	
C14.	Life Sciences Experiments Tool Kits	

Table 3-5

SUPPORT EQUIPMENT LIST FOR COSTING VARIOUS MAN-MACHINE MODES (Continued)

D.	Command, Control, Communication, and Data Management Equipment	(3.4.6)
D1.	Control/Display for Remote Gimbals	
D2.	Control/Display for Remote Cameras (TV and Photo)	
D3.	Automatic Adjustment for Control of Remote Equipment	
D4.	Voice Intercommunication	
D5.	Control and Display Activation and Monitoring Equipment, Keyboard	
D6.	Hardware for Accepting Remote Commands	
D7.	Display and Software for Record Keeping, Procedures, Schedules, and Maintenance	
D8.	Computer Programmed for Command and Control of a Specific Function/Task by Artificial Intelligence	
D9.	Encode/Decode Data Equipment	
D10.	Data Computation and Reduction Equipment	
D11.	Input/Output Data Buffer Equipment	
D12.	Central Timing Unit	
D13.	NSSC Interface Management Unit	
D14.	Remote Units	
D15.	CDMS Central Unit	
D16.	High-Rate Recorder	
D17.	Low-Rate Recorder	
D18.	NSSC-II Computer	
D19.	Ku-Band Communication Equipment	
D20.	S-Band Communication Equipment	
D21.	Low-Gain Antennas	
D22.	RF Transfer Switcn	
D23.	Support Instrumentation/Sensor Equipment	
D24.	Telemetry Unit	
D25.	Payload Command and Data Acquisition Unit	

Table 3-5

SUPPORT EQUIPMENT LIST FOR COSTING VARIOUS MAN-MACHINE MODES (Continued)

E.	Orbital Mobility Systems	(3.4.8)
E1.	Orbital Maneuvering Vehicle (OMV)	
E2.	Orbital Transfer Vehicle (OTV)	
E3.	Telepresence Manipulator System (TMS)	
F.	Operating Systems Software	(3.4.9)
F1.	User Interface	
F2.	Facility Readiness Test (Integration)	
F3.	Dynamic Scenario Profile Generation	
F4.	Command Generation	
F5.	Telemetry Data Handling	
F6.	Input/Output	
F7.	Test Data Generation	
F8.	Data Base Generation/Maintenance	
F9.	Data Reduction	
F10.	Support Software	
F11.	Software for Command and Control Hardware Controlled from a Remote Ground or Orbital-Based Work Station	
F12.	Software for Computer Programmed for Command and Control of a Specific Function/Task by Artificial Intelligence	

essentially constant regardless of the level of complexity of the task required. Since only relative costs were to be determined, this line of reasoning permitted different examples to be used with different activities.

To aid in the process, an evaluation sheet, shown in Figure 3-12, was developed. For each of the generic activities, a specific example was selected to analyze for each of the applicable man-machine categories. The support equipment items were then identified that would be required in order to accomplish the assigned task in each man-machine category. For example,

SUPPORT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 1	CATEGORIES OF MAN-MACHINE INTERACTIONS						
					SUPERVISED		
ACTIVATE/INITIATE SYSTEM OPERATION	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	GROUND	ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED (SEE TABLE E-1)						
I V A	A1 C8	A1 C8 C13	A1 C9 C13	A1 C10 D5 D6	A2 A5 A6 D5 D6 F11	A1 D5 D6 F11	A2 A3 A4 A5 A6 D3 D6 D7 D8,F12*
E V A	A1 B1 C8 C13	A1 B1 C8 C13	A1 B1 C9 C13				

EXAMPLE - Activate Camera/T.V. Image Gathering Equipment

MANUAL - 35 mm Camera
SUPPORTED - 35mm Camera with Auto Advance
AUGMENTED - 35mm Camera with Auto Timing Sequence
TELEOPERATED - RMS TV Camera
SUPERVISED GROUND - TV Camera
SUPERVISED ON-ORBIT - TV Camera
INDEPENDENT - Satellite Image Equipment

*Considered as one item of support equipment
D8 - Computer Hardware
F12 - Associated Software

Figure 3-12. Typical Support Equipment Evaluation Sheet

referring to Figure 3-12, the specific example selected for "Activate/Initiate System Operation" is the "activation of camera/TV image-gathering equipment." Accomplishing this task in the manual category through an EVA mode of operation involves four items of support equipment. Referring to Table 3-5, the four items required were identified as follows:

A1 - Space Station Facility
B1 - Extravehicular Mobility Unit (EMU)
C8 - Support Equipment, Experiment Specific, $10,000
(35mm Camera Equipment)
C13 - Restraints to Support Manned Activities

This support equipment identification process continued through the rest of the applicable man-machine categories.

In the Supported mode, the system might include a motor-driven advance. In the Augmented mode, the adjustment of the lens opening and timing sequence might be automated. In the Teleoperated mode, the camera would be adjusted by remote command. In the Supervised mode, the initiation of the picture sequences would be commanded from a remote location but the activation of all operations would be preprogrammed. In the Independent mode, the system would be activated by a self-contained sensor system.

Although the performance times for IVA and EVA operations were judged to be similar as discussed in Section 3.2, the support equipment items necessary for IVA and EVA operations were usually different. Accordingly, both IVA and EVA support requirements were identified when applicable, as illustrated in Figure 3-12.

The 37 activity support equipment evaluation sheets will be found in Appendix E. Each sheet contains the table of required support equipment items for each of the man-machine categories for both IVA and EVA modes of operation where applicable. Also the specific examples that were chosen to represent the generic space activity are indicated on the sheets for each of the seven man-machine categories.

3.4 ECONOMICS OF HUMAN ACTIVITIES IN EARTH ORBIT

The development of comparative cost data for use in evaluating the economic advantages and disadvantages of the alternative modes of man-macnine interactions consisted of two steps. These steps were to (1) identify the significant factors influencing space activity costs, and (2) establish a usage cost methodology for all elements included in these identified cost factors. The activity support requirements described in Section 3.3 provided the initial definiton of the cost factors. Once a cost methodology was established, the relative cost differences in accomplishing each of the generic classes of activities by each of the alternative man-machine modes could be determined.

Activity support requirements were found to fall into two general groups. These two groups can be identified as (1) time related and (2) frequency-of-use related requirements. The time related group is characterized by the requirement for a support element to be used over an estimated activity timeline and includes use of the space station facility, the ground control and data handling facilities, the tracking and data relay satellite system, and the EVA support items. The frequency-of-use related group is characterized by the requirement for a multiuse support item needed to perform an activity and includes tool kits and mechanical support equipment; command, control, communication and data management equipment; unmanned platform basic resources; orbital mobility systems; and operating systems software.

The approach used to develop usage cost methodology for the above listed support requirements is described in the following paragraphs, starting with the time related group followed by the frequency-of-use related group.

3.4.1 Space Station Facility

No firm guidelines or charge policies for developing operational user costs in the Space Station era are currently available from government sources. Accordingly, the general approach taken in this study was to establish a mission-related incremental cost as the basis for charging space activities requiring direct human involvement at the space station. The incremental cost was defined as the cost difference between full

mission-support capability and "zero mission" man-in-space-only capability. The basic space station sizing parameters (crew size, number of modules, electrical power, communications data rate, and thermal control) were defined for both a full capability IOC station and a hypothetical "zero mission" station that supported no payloads and was required only to maintain itself in orbit. The differences in design parameters between the "zero mission" and the "full capability" configuration are illustrated in Figures 3-13 and 3-14. Activity costing factors are presented in Table 3-6.

The MDAC computerized space facility cost prediction model was then run with these two sets of values to establish the incremental cost associated with the support of potential users or specific missions. The cost difference between the zero capability and the full capability facility was adjusted to exclude design and development cost assuming that nonrecurring cost should not be included when developing a baseline for estimating user charges. A ten-year life was assumed for the hardware represented by the resulting

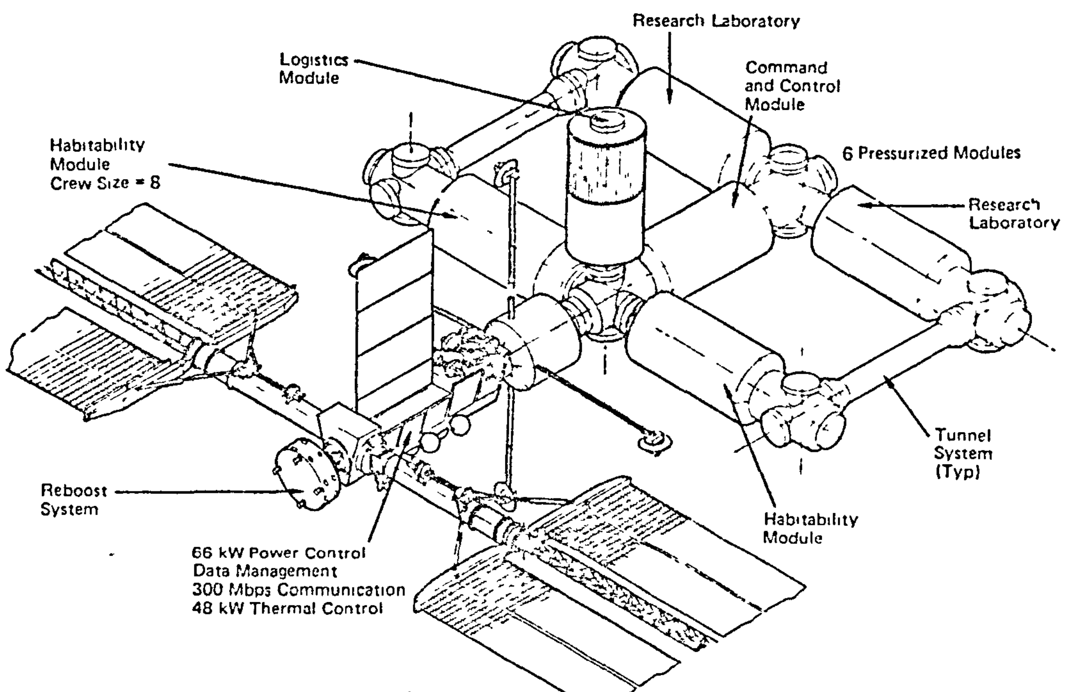


Figure 3-13. Space Station (Full Capability)

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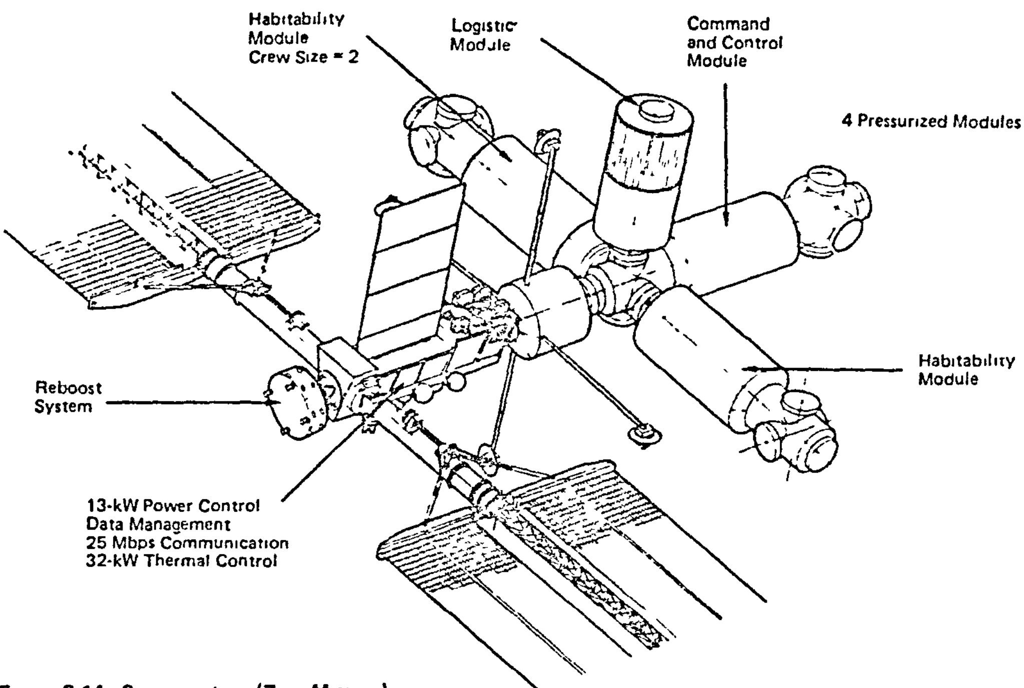

Figure 3-14. Space Station (Zero Mission)

Table 3-6
ACTIVITY COSTING FACTORS

Cost elements that are primarily a function of time use (cost/minute)
• Space station facilities and logistics operations • Ground control and data handling facilities • Tracking and data relay satellite system • EVA support items
Cost elements that are primarily a function of number (N) of uses (cost/use)
• Tool kits and mechanical support equipment • Command, control, communications and data management equipment • Unmanned platform resources • Orbital mobility systems • Operating systems software

incremental space station facility cost. A straight line amortization results in an average cost per year which when divided by available operating man-hours per year yields a cost of $10,427 per operating hour for manned utilization of the space station pressurized volume and utility services. This calculation is illustrated in Table 3-7.

Table 3-7
PRESSURIZED VOLUME AND UTILITY SERVICES COST(1)

	FULL CAPABILITY STATION ($ x 10^6)	ZERO MISSION STATION ($ x 10^6)	INCREMENTAL COST ($ x 10^6)
Simulator/Development Hardware	1380	794	586
Flight Hardware	2244	1366	878
Total	3624	2160	1464

Amortized Incremental Cost = $\frac{\$1464M}{10 \text{ years}}$ = \$146.4M/yr

Cost Per Operating Hour = $\frac{\$146.4M/yr}{14{,}040 \text{ hrs/yr}^{(2)}}$ = \$10,427/hr

(1) Production cost only; excludes design and development cost.
(2) 6 men x 9 hrs/day x 5 days/wk x 52 wks/yr = 14,040 hrs/yr.

A similar incremental cost approach was used to estimate logistics operations (replacement spares, consumables, maintenance, and repairs) associated with the space station facility. This resulted in a cost of $12,201 per operating hour for space station logistics operations. The MDAC cost model run generated the values for this calculation and these values are summarized in Table 3-8.

The incremental cost for logistics transportation was determined by allocating the Space Shuttle flight cost in proportion to the ratio of

Table 3-8
LOGISTICS OPERATIONS COST

	FULL CAPABILITY STATION ($ x 10^6)	ZERO MISSION STATION ($ x 10^6)	INCREMENTAL COST ($ x 10^6)
Replacement Spares & Consumables	261.5/yr	129.7/yr	131.8/yr
Maintenance & Repairs	97.8/yr	58.3/yr	39.5/yr
Total	359.3/yr	188.0/yr	171.3/yr

$$\text{Cost Per Operating Hour} = \frac{\$171.3M/yr}{14{,}040\ hrs/yr} = \$12{,}201/hr$$

logistics operations incremental cost to full capability cost with a further cost-sharing adjustment. This resulted in a cost of $9,402 per hour calculated as follows:

Assuming 20% sharing with other payloads and 4 STS flights per year;

Total Cost = $86M/flt x 80% x 4 flts/yr = $275.2M/yr

$$\text{Allocation factor (from logistics operations)} = \frac{\$171.3M}{\$359.3M} = 48\%$$

Incremental Cost = $275.2M/yr x 48% = $132M/yr

$$\text{Cost per Operating Hour} = \frac{\$132M/yr}{14{,}040\ hrs/yr} = \$9{,}402/hr$$

In addition to the three major elements of space station facility cost described above, estimates were added for use of airlock and safe haven resources to complete the space station facility usage charge. Based on data contained in the MDAC cost data bank, these two items were estimated at $164 per hour and $328 per hour, respectively. The sum of all five elements amounts to $32,522 per hour (or $542 per minute) for use of the space station facility. This value is summarized in the Table 3-9.

Table 3-9
SPACE STATION FACILITY
COST PER OPERATING HOUR FOR ACTIVITIES REQUIRING DIRECT HUMAN INVOLVEMENT IN SPACE
(1984 Dollars)

Pressurized Volume & Utility Services	$10,427
Logistics Operations	12,201
Logistics Transportation	9,402
Airlock	164
Safe Haven	328
Total Space Station Facility	$32,522

3.4.2 Ground Control and Data-Handling Facilities

This category within the time-related group includes the ground control center, payload control center, and data-handling facility. The time-related charges for use of these facilities is based on a ten-year amortization of production cost plus annual operations cost allocated over the estimated annual availability time. The production and operations cost data were obtained from the MDAC Space Platform Ground System Study*. An example of the usage charge calculation for the ground control center is as follows:

Amortized Production Cost	$3.874M ÷ 10 yrs =	$ 0.387M
Annual Operations Cost		3.345M
Total Annual Cost		$3.732M

Annual Availability Time = 480 minutes per day (8 hours) x 5 days per week x 52 weeks per year = 124,800 minutes

$$\text{Cost per Minute} = \frac{\$3.732M/yr}{124,800\ min/yr} = \$30/min$$

* Ford Aerospace and Communications Corporation, Space Platform Ground System Study, Baseline Data Package, prepared under MDAC Contract NAS8-33955, July 1982 (see Reference 70).

Costs per minute for the other two facility items were calculated in a similar manner. The results of these calculations are summarized in Table 3-10.

Table 3-10
GROUND CONTROL AND DATA-HANDLING FACILITIES
USER SERVICE CHARGE PER MINUTE
(1984 Dollars)

1.	Ground Control Center, Baseline System	$30/min
2.	Payload Control Center, Baseline System	46/min
3.	Data Handling Facility, Baseline System	11/min

3.4.3 Tracking and Data Relay Satellite System (TDRSS)

The time-related charge for use of the TDRSS is $110 per minute. This was obtained from the NASA Management Instruction, "Tracking and Data Relay Satellite System (TDRSS), Use and Reimbursement Policy for Non-U.S. Government Users," March 1983.

3.4.4 EVA Support Items

This category within the time-related group includes the Extravehicular Mobility Unit (EMU), the Manned Maneuvering Unit (MMU), and the Remote Manipulator System (RMS). The time-related charges for use of these items is based on a ten-year amortization of production cost plus annual operations cost allocated over the estimated annual availability time. An example of the usage charge calculation for the EMU is as follows:

Amortized Production Cost	$2.0M ÷ 10 yrs =	$ .2M
Annual Operations Cost		2.0M
Total Annual Cost		$2.2M

Annual Availability Time = 540 minutes per day (9 hours) x 5 days per week x 52 weeks per year = 140,400 minutes

$$\text{Cost Per Minute} = \frac{\$2.2\text{M/yr}}{140{,}400\ \text{min/yr}} = \$15.67\text{/min}$$

Costs per minute for the other two items were calculated in a similar manner. The results of these calculations are summarized in Table 3-11.

Table 3-11
EVA SUPPORT ITEMS USER SERVICE CHARGE PER MINUTE
(1984 Dollars)

Extravehicular Mobility Unit (EMU)	$15.67/min.(1)
Manned Maneuvering Unit (MMU)	53.33/min.(1)
Remote Manipulator System (RMS)	121.00/min.(2)

(1) Contacts with JSC Personnel (1983 - 1984).
(2) Quote from Spar Ltd., Canada, 1983.

3.4.5 Tool Kits and Mechanical Support Equipment

This first category within the frequency-of-use related group includes special tools, test sets, refurbishment kits, restraints, etc., which could be used to support a number of different activities and would probably be reused many times during their operational life. The cost per use for these items is based on an approach that employs a quantity-adjusted amortization of unit production cost combined with a dollar-value-adjusted operations cost. The following equation is used to estimate the usage charge for the equipment items as a function of number of anticipated uses.

$$\text{Cost/Use} = \frac{C}{N^{0.848}} + 0.25C^{0.8}$$

where C = initial production unit cost of item
where N = number of times an activity is performed using the item

The first term of this equation represents an amortization of the initial unit cost (cost divided by number of uses). It will be noted that the number of uses (N) is adjusted by an exponent whose value is 0.848. This adjustment is applied to account for the greater risk of equipment failure and potential replacement as the item is continually used and refurbished over its entire

useful life. The 0.848 exponent is related to a 90% cost-reduction curve which is commonly used in cost/quantity relationships. In the present application, doubling the number of times an activity is performed results in an average cost which is 90% of the previous cost. As an example, a change in frequency from 10 to 20 (a factor of 2) would reduce the average unit cost as follows:

$$(2^{0.848}) \div 2 = 0.90 \text{ or } 90\% \text{ reduction}$$

Applying this approach to the computation of equipment cost amortization results in a progressively greater value for the amortization of initial cost compared to a straight-line amortization schedule, as the number of uses increases.

The second term of this equation represents a recurring operations cost per use for maintenance and refurbishment, calculated as a percentage of initial equipment cost. The scaling adjustment applied here (the exponent whose value is 0.8) results in a decreasing percentage of initial cost as the initial cost becomes larger. This rationale allows for an adequate refurbishment charge for a relatively low cost item and also prevents an excessive charge being applied to a very high cost item. As an example, the percentage charge on a $10,000 item is approximately 4% whereas the percentage on a $10,000,000 item is only about 1%. These percentages are judgment factors based on related analysis from previous studies. The base production unit cost data and data sources for all items in this category are summarized in Table 3-12.

3.4.6 Command, Control, Communication, and Data Management Equipment

This frequency-of-use category includes control/display panels, computers, keyboards, data storage equipment, intercom devices, servo actuators, encoders, decoders, and support instrumentation. All are assumed to be multiuse items capable of supporting a number of different acivities. The same cost per use equation described under Tool Kits and Mechanical Support Equipment is used to estimate the usage charge for these items. The base production unit cost data and data sources for all items in this category are summarized in Table 3-13.

Table 3-12

TOOL KITS AND MECHANICAL SUPPORT EQUIPMENT
PRODUCTION UNIT COSTS
(1984 Dollars)

1.	Power Tool, Portable	$ 52,000	(2)
2.	Tool Kits, Manual	16,000	(2)
3.	Gas Recharge Kit	76,000	(1)
4.	Fluid Recharge Kit	152,000	(1)
5.	Test Set, Alignment/Calibration, Portable	315,000	(1)
6.	Test Set, Electrical Checkout	210,000	(1)
7.	Surface Coating/Refurbishment Apparatus	456,000	(1)
8A.	Support Equipment, Experiment Specific	10,000	(3)
8B.	Support Equipment, Experiment Specific	50,000	(3)
8C.	Support Equipment, Experiment Specific	250,000	(3)
8D.	Support Equipment, Experiment Specific	1,000,000	(3)
9.	Cherry Picker with Work Platform (RMS)	645,000	(2)
10.	Restraints to Support Manned Activities	124,000	(2)
11.	Life Sciences Experiments Tool Kits	34,000	(3)

(1) McDonnell Douglas Astronautics Company, Power System Design Concept Study, Phase C/D Cost Estimate, DR-6 Final Report, Contract NAS8-33955, June 1981.
(2) Essex Corporation, Analysis of Large Space Structures Assembly, NASA Report No. 3751, December 1983.
(3) McDonnell Douglas Astronautics Company, In House Studies and Engineering Judgment.

3.4.7 Unmanned Platform Basic Resources

This category provides a usage charge for the basic resources portion of the unmanned platform (subsystem capability not required to support payloads) where unmanned support is required to perform a particular activity. The MDAC cost model predicts a total platform production cost of $364.66 million or $36.466 million per year asuming a ten-year amortization. The ratio of platform subsystem power requirements to total power requirements is 2.5 kW/14.0 kW or 0.17857. Applying this ratio to the $36.466 million per year total results in an allocation of $6.512 million per year for platform basic resources.

A current platform mission analysis shows an average of 1260 activities per year involving platform usage. The average cost per use based on these values is $6.512M/1260 = $5168/use. Applying the quantity adjustment exponent

Table 3-13

COMMAND, CONTROL, COMMUNICATION, AND DATA MANAGEMENT EQUIPMENT
PRODUCTION UNIT COSTS
(1984 Dollars)

1.	Control/Display for Remote Gimbals	$155,000	(1)
2.	Control/Display for Remote Cameras (TV and Photo)	108,000	(1)
3.	Automatic Adjustment or Control of Remote Equipment	608,000	(1)
4.	Voice Intercommunication	381,000	(2)
5.	Control and Display Activation and Monitoring Equipment, Keyboard	175,000	(1)
6.	Hardware for Accepting Remote Commands	75,000	(3)
7.	Display and Software for Record Keeping, Procedures, and Schedules Maintenance	200,000	(1)
8.	Computer Programmed for Command and Control of a Specific Function/Task by Artificial Intelligence	1,521,000	(1)
9.	Encode/Decode Data Equipment	68,000	(3)
10.	Data Computation and Reduction Equipment	380,000	(1)
11.	Input/Output Data Buffer Equipment	141,000	(1)
12.	Central Timing Unit	1,305,000	(1)
13.	NSSC Interface Management Unit	770,000	(1)
14.	Remote Units	324,000	(1)
15.	CDMS Central Unit	567,000	(1)
16.	High-Rate Recorder	2,418,000	(1)
17.	Low-Rate Recorder	495,000	(1)
18.	NSSC-II Computer	1,521,000	(1)
19.	Ku-Band Communication Equipment	7,029,000	(1)
20.	S-Band Communication Equipment	1,570,000	(1)
21.	Low-Gain Antennas	405,000	(1)
22.	RF Transfer Switch	81,000	(1)
23.	Support Instrumentation/Sensor Equipment	3,108,000	(1)
24.	Telemetry Unit	68,000	(1)
25.	Payload Command and Data Acquisition Unit	432,000	(1)

(1) McDonnell Douglas Astronautics Company, Power System Design Concept Study, Phase C/D Cost Estimate, DR-6 Final Report, Contract NAS8-33955, June 1981.
(2) McDonnell Douglas Astronautics Company, Manned Orbital Systems Concepts Study, Final Report - Programmatics for Extended Duration Missions, Contract NAS8-31014, Report No. MDC G5919, September 1975.
(3) McDonnell Douglas Astronautics Company, Payload Assist Module (PAM) Program, Actual Cost Experience for Similar Items.

of 0.848 described under tool kits results in a calculated first use (C) of \$2.2 million as follows:

$$\frac{C}{1260^{0.848}} = \$5168$$

$$C = \$2.2 \text{ million}$$

The general equation for cost per use as a function of number of uses (N) is then

$$\frac{\$2.200M}{N^{0.848}}$$

Operations cost was estimated to be 25% of the production cost relationship or

$$\frac{\$0.550M}{N^{0.848}}$$

3.4.8 Orbital Mobility Systems

This frequency-of-use category includes the Orbital Maneuvering Vehicle (OMV), the Orbital Transfer Vehicle (OTV), and the Telepresence Manipulator System (TMS). These are all complex, expensive systems that will be designed for multiple applications and large numbers of uses. The cost per use for these items is based on an approach similar to that described under Unmanned Platform Basic Resources. A ten-year amortization of production unit cost was again used along with an assumption of 250 uses per year. An example using the TMS shows the following calculations:

Amortized Annual Production Cost = \$41.0 million ÷ 10 years = \$4.1M/yr
Average Cost Per Use = \$4.1M ÷ 250 = \$16,400/use
Calculated First Use (C) = \$16,400 x $250^{0.848}$ = \$1.771M
Operations First Use = 0.25 x \$1.771M = \$0.443M

These calculated values amount to 0.0432 and 0.0108 times production unit cost as follows:

Production First Use = \$1.771M ÷ \$41.000M = 0.0432
Operations First Use = \$0.443M ÷ \$41.000M = 0.0108

Since the same ten-year amortization and 250 uses per year is used for all three items in this category, the following general equation can be used to estimate the usage charge for these items as a function of number of anticipated uses:

$$\text{Cost/Use} = \frac{0.0432C}{N^{0.848}} + \frac{0.0108C}{N^{0.848}}$$

where C = initial production unit cost of item and N = number of times an activity is performed using the item.

The base production unit cost data and data sources for the three items in this category are summarized in Table 3-14.

Table 3-14
ORBITAL MOBILITY SYSTEMS
PRODUCTION UNIT COSTS
(1984 Dollars)

1.	Orbital Maneuvering Vehicle (OMV)	$ 65,000,000 (1)
2.	Orbital Transfer Vehicle (OTV)	131,000,000 (2)
3.	Telepresence Manipulator System (TMS)	41,000,000 (3)

(1) Contacts with JSC Personnel (1983 - 1984).
(2) Consensus of Previous NASA and Contractor Studies.
(3) Essex Corporation, Analysis of Large Space Structures Assembly, NASA Report No. 3751, December 1983.

3.4.9 Operating Systems Software

Software items are also charged as a function of number of uses, but a slightly different approach was employed and may be described as follows:

$$\text{Cost/Use} = \frac{C}{N} + \frac{0.55C}{N^{0.848}}$$

where C = initial software development cost and N = number of times an activity is performed using the software element.

The first term of this equation represents a straight-line amortization of the initial software development cost. Although the general cost analysis groundrule was to amortize production cost only, software does not have an identifiable production cost and its development cost is considered comparable to hardware production cost as a base for amortization. The software items included in support requirements are all general, multimission systems and do not include payload-specific software. No cost/quantity adjustment was applied for risk of failure since the hardware adjustment did not appear applicable in the case of repetitive use of software. The second term of the equation represents a recurring operations cost-per-use for software maintenance. Data from the 1982 Space Platform Ground System Study indicate that software maintenance at a nominal 100 uses over 10 years amounts to about 110% of original software development cost. Since software maintenance is related to time as well as number of uses, it was assumed that the minimum software maintenance charge for one use over ten years would be 50% of the nominal 10-year cost, or 55% of initial software development cost. This starting value was scaled in relation to quantity using the same 0.848 exponent application described under equipment cost amortization. This results in an increasingly greater total software maintenance operations cost as the number of uses increases. The base software development cost data and data sources for this category are summarized in Table 3-15.

3.4.10 Cost Methodology Application

Application of the above described cost methodology, shown schematically in Figure 3-15, consists of (1) obtaining inputs of support requirement elements from the activity definition sheets and mean times to perform from the activity timeline sheets, (2) running the appropriate equations with the applicable unit cost and cost per hour data for a representative number of times performed, and (3) plotting the composite cost/quantity calculations in the form of cumulative cost versus frequency of use curves. The results of the cost methodology application consist of 37 sets of cost curves which summarize, for each of the 37 generic space activities, the relative economics associated with the performance of each activity by the seven alternative modes of man-machine interaction. All 37 sets of cost versus frequency of use curves are presented in Appendix F. Two variations in the data plotted are presented for each activity. The first variation excludes operations costs

Table 3-15
OPERATING SYSTEMS SOFTWARE
SOFTWARE DEVELOPMENT COSTS
(1984 Dollars)

1.	User Interface	$ 1,654,000	(2)
2.	Facility Readiness Test (Integration)	1,654,000	(2)
3.	Dynamic Scenario Profile Generation	6,565,000	(2)
4.	Command Generation	3,283,000	(2)
5.	Telemetry Data Handling	4,911,000	(2)
6.	Input/Output	1,654,000	(2)
7.	Test Data Generation	465,000	(2)
8.	Data Base Generation/Maintenance	956,000	(2)
9.	Data Reduction	465,000	(2)
10.	Support Software	956,000	(2)
11.	Software for Command and Control Hardware Controlled from a Remote Ground or Orbital-Based Work Station	8,478,000	(1)
12.	Software for Computer Programmed for Command and Control of a Specific Function/Task by Artificial Intelligence	16,956,000	(1)

(1) McDonnell Douglas Astronautics Company, Power System Design Concept Study, Phase C/D Cost Estimate, DR-6 Final Report, Contract NAS8-33955, June 1981.

(2) Ford Aerospace and Communications Corporation, Space Platform Ground System Study, Baseline Data Package, prepared under MDAC Contract NAS8-33955, July 1982.

associated with equipment refurbishment, platform operations and maintenance, orbital mobility systems operations, and software maintenance. The second variation includes these operations costs along with all applicable time-related usage charges and frequency-of-use related production cost amortization charges. The inclusion of operations costs probably represents a more equitable approach to establishing user charges. The data excluding operations cost are presented to recognize the current generalized level of

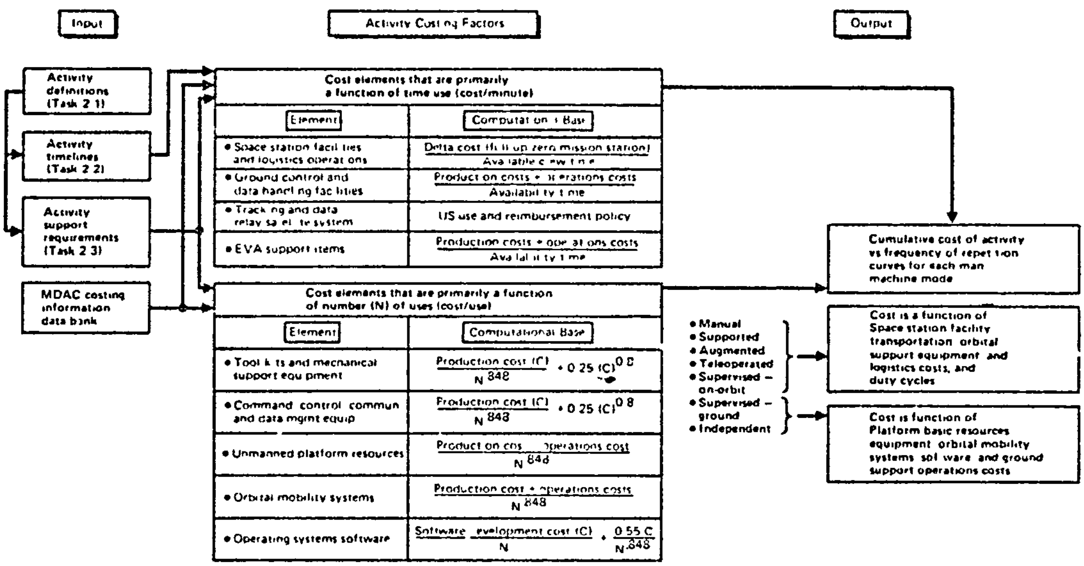

Figure 3-15. THURIS Cost Methodology

operations cost analysis and provide an easy means to substitute better cost data resulting from future detailed operations analysis.

Figure 3-16 illustrates the application of the cost methodology for one of the 37 generic space activities, "Implement Procedures/Schedules." The activity definition and timeline sheets (see Appendices D and E) for this activity identify the specific support requirement items and mean times to perform this activity in each of the seven modes of man-machine interaction. The costs per use for time-related items (see Figure 3-15) are calculated as the product of the mean time to perform (from the activity timeline sheet) and the applicable cost per hour or minute (from Sections 3.4.1, 3.4.2, 3.4.3, and 3.4.4). The costs per use for frequency-of-use related items (see Figure 3-15) are calculated using the applicable production unit costs or software costs entered into the appropriate equations documented in Sections 3.4.5, 3.4.6, 3.4.7, 3.4.8, and 3.4.9. Cumulative costs are calculated for all

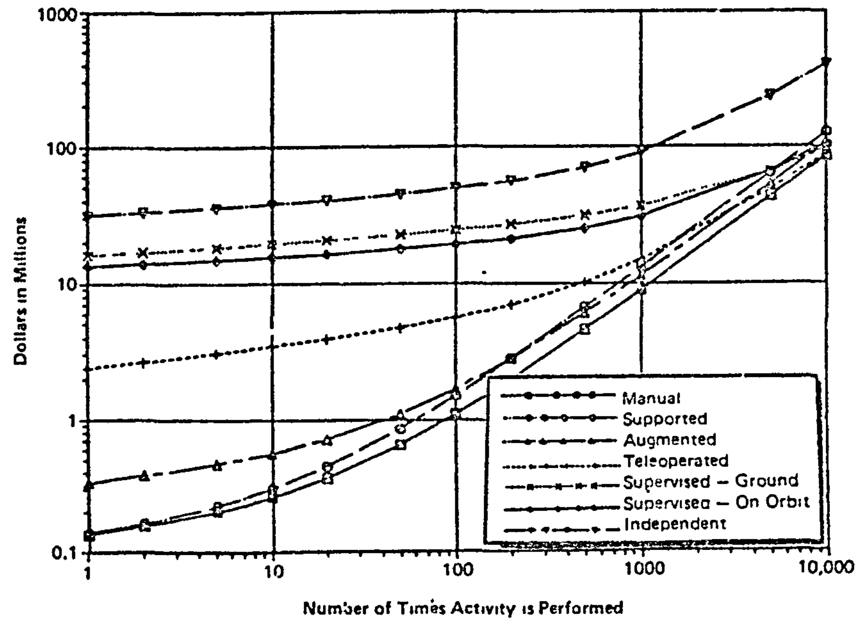

Figure 3-16. Activity 20–Implementation Procedures/Schedules Cumulative Cost vs. Repetitions Including Operations

specified items at representative quantities of 1, 2, 5, 10, 20, 50, 100, 500, 1000, 5000 and 10,000 to provide sufficient data points to plot the composite cost versus frequency-of-use curves for each of the seven man-machine interaction modes.

3.4.11 Observations

Although the implementation costs for each individual activity in each man-machine interaction mode are somewhat different, a rather significant observation is that the cost level for direct human involvement (manual, supported, augmented, or teleoperated modes) generally remains considerably lower than the cost for remote human involvement (supervised and independent modes) over a large number of times that the activity might be performed (1 to 1000 times). As may be noted on Figure 3-16, the cost differentials were generally observed to span two orders of magnitude when only a few activations are required (1 to 10) but narrowed to one order of magnitude when the number of activations approached 1000. For the most activities, the manual mode can be performed in a relatively short time period (less than 1 hour) with only

minimal inexpensive support equipment. The $32,522 per hour space station facility charge, although a significant factor if lengthy times are involved, remains at a relatively low cost level for short time periods until the frequency of use approaches 1000. Performing activities in the independent or teleoperated modes requires, in most cases, a relatively expensive initial investment in support equipment and software which does not compare favorably with the manual mode unless amortized over a large number of uses.

Variations from the patterns observed in Figure 3-16 occurred for a few activities where unusual equipment or timeline requirements were specified for a particular mode of man-machine interaction. For example, the relatively high cost for Activities 36 and 37 - Transport Loaded/Unloaded (see Figure 3-17) in the teleoperated mode occurs because the average time to acomplish this class of activity with a teleoperator was estimated to be 60 minutes as predicated upon the timeline data of Subtask 2.2. Another example is Activity 32 - Replace/Clean Surface Coatings (see Figure 3-18) where the manual and supported modes also become relatively costly when the number of times the

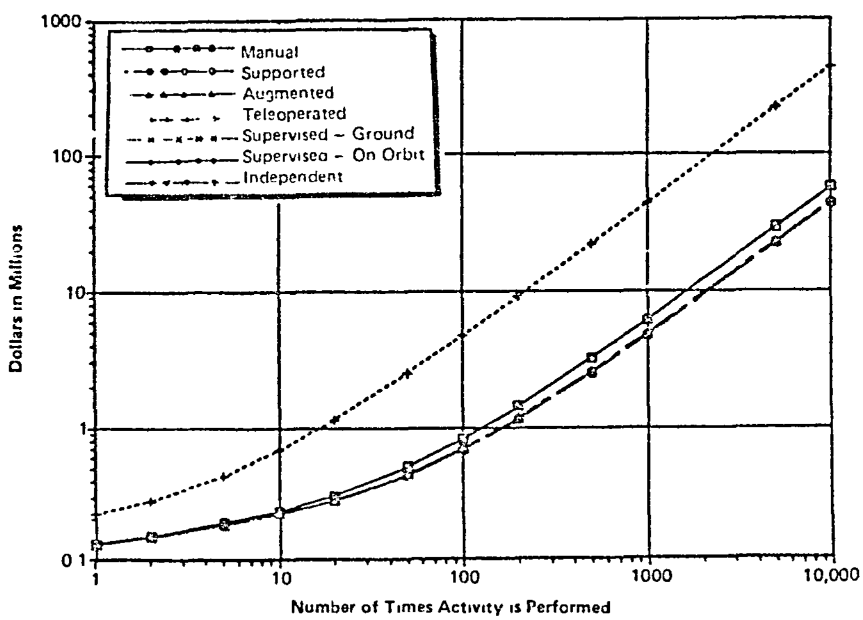

Figure 3-17. Activity 36 – Transport Loaded Cumulative Cost vs. Repetitions Including Operations

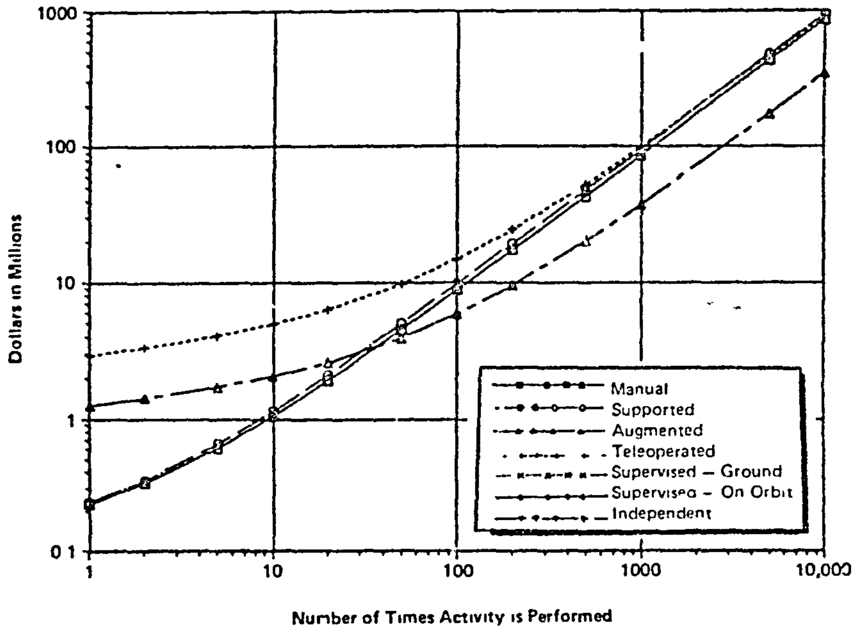

Figure 3-18 Activity Number 32 – Replace/Clean Surface Coatings Cumulative Cost vs. Repetitions Including Operations

activity is to be performed increases to one hundred or more. Again, this was due primarily to the average time (150 minutes) required for this activity in the manual mode as derived from the timeline data developed in Subtask 2.2.

A principal criterion used to identify the critical technology issues to be considered in Task 3 is the need to improve productivity and to thereby reduce the cost of future space operations. One of the highest cost activities identified to date, especially in the supervised and independent modes of operation, is Activity Number 27 - Problem Solving/Decision Making and Data Analysis (Figure 3-19). The cost in this case is due in large part to the requirements for relatively expensive sensors, instrumentation, and software needed when operating in the supervised and independent modes. This suggests the need for a better understanding and coupling of artificial and human intelligence and the development of techniques for the effective utilization of "expert" systems. On the other hand, in Activity 32 (see Figure 3-17), the high cost of the manned and supported modes suggests the need for improvements in the process technology for cleaning optical surfaces and/or coatings in space.

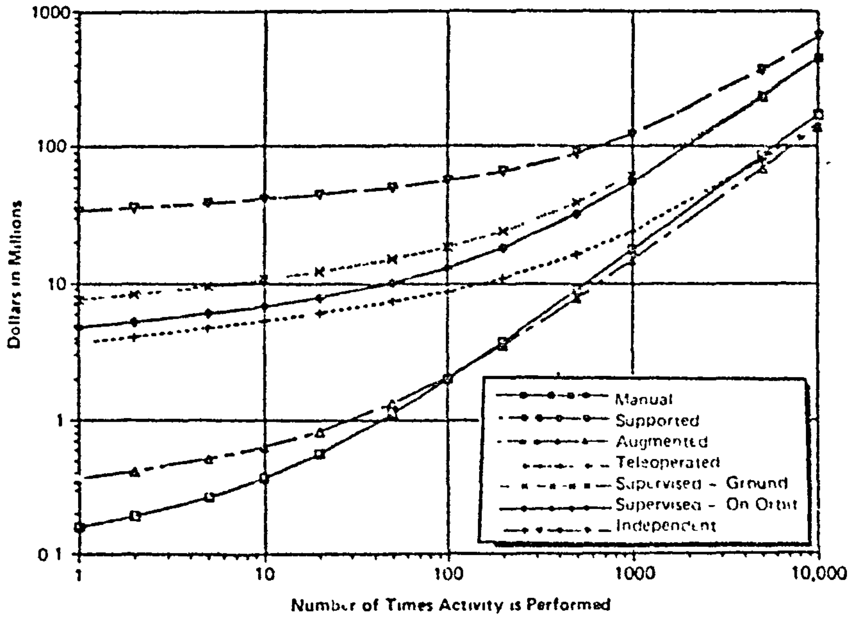

Figure 3-19. Activity Number 27 — Problem Solving/Decision Making/Data Analysis Cumulative Cost vs. Repetitions Including Operations

3.5 EVALUATION

In Section 3.1, a generic set of mission activities was described based upon a review of past and proposed space missions. This generic set of activities was designed to provide the building blocks from which future space missions could be synthesized. In Section 3.2, comparative timeline data for each of the basic activities were developed. In Section 3.3, the support equipment requirements associated with each activity implementation option were identified and this information in turn was used in Section 3.4 to prepare comparative cost data associated with the provision, support, and utilization of various degrees of direct human involvement in future space missions.

The techniques described and the information developed in the preceding sections provide the framework for developing a methodology comparative costing. It is intended that this methodology provide a basis for evaluating the impact of varying degrees of human involvement on the effectiveness and economy of satisfying the requirements of future space projects. In

accomplishing this goal, it was believed that the comparative data would be most useful if they were expressed in a tabular or graphic format. Factors that need to be considered in formulating a strategy for evaluating the impact of varying degrees of human involvement in satisfying the activity requirements are (1) the performance limits associated with direct or indirect human involvement, (2) the number of times a specific activity is to be performed, (3) and the number of different activities that are required to be performed in the operational sequence being examined. The limiting factors on direct human involvement are primarily associated with sensing (whether stimuli are within or outside of the range of human sensory capability); information processing (whether or not the complexity of the information to be processed requires supplemental aids); and action (whether or not the action required is within the range of human motor responses). These limiting factors are well documented, as discussed in Section 2 and can be addressed in checklist fashion in the initial conceptual design phase of the program development process.

In many cases, alternative modes of man-machine interaction could satisfy performance requirements. The issue then becomes one of cost; i.e., which of the applicable man-machine modes of interaction is the most cost effective.

In addressing this issue, the most important factors are the number of times a specific activity is to be performed, and the number of different activities that are required to be performed in the operational sequence. Conventional wisdom would suggest that even if a given activity were capable of being performed in a manual mode, the cost of a man/hour or man/minute in space is so high that if that activity were required to be repeated a number of times, a cross-over point would quickly be reached where it would be most cost effective to implement a more automated approach to the activity performance. In similar fashion, it can be reasoned that the human operator is basically a single channel mechanism and cannot be expected to perform multiple activities simultaneously although the activities might be performed serially if the performance time permits.

In order to provide a comparative base for examining the cost effectiveness of the various man-machine modes and to establish the cross-over points where one mode becomes more cost effective than another, it was

believed desirable to equate the relative cost of performing each activity by each of the modes of implementation to a common dollar base, and to thereby establish a family of equal cost curves based upon the following relationship:

$$\underline{\text{Equation One}} \qquad \overset{(A)}{\begin{bmatrix}\text{Cost for Performing}\\ \text{an Activity "N"}\\ \text{Times in the}\\ \text{Direct Manual Mode}\end{bmatrix}} = \overset{(B)}{\begin{bmatrix}\text{Cost for Performing}\\ \text{an Activity "N"}\\ \text{Times in an}\\ \text{Indirect Mode}\end{bmatrix}}$$

If $A > B$, then an indirect mode should be considered. If $A < B$, then a direct mode should be considered. If $A = B$, the decision must be based on other criteria. One additional factor must be considered in establishing these cost relationships, however, and that is the total number of activities required in the operational sequence. In dealing with the cost of direct manual involvement in the performance of any set of activities, the most significant factor is the crew time required and the cost per unit of crew time.

The more activities that are required, the more time is required, and the higher the cost. This is true of the manual, supported, augmented and teleoperated modes of operation. In the case of the operational modes where the human involvement is more indirect (i.e., the supervised-ground, the supervised-on-orbit, and the independent modes), the principal contributor to the cost of performing a set of activities is more directly dependent upon the cost of the resources and the supporting equipment items required to perform each activity in orbit rather than upon the time required to accomplish the activity. This means that in the modes requiring indirect human involvement, the reduction of cost due to the potential of sharing common equipment items and common resources can be a significant factor in the cost equation.

A common finding in previous studies has been that there is a great deal of commonality among the equipment items required to support a broad spectrum of missions, or space activities. That is, the first few activities examined will introduce a number of new equipment requirements. This equipment, however, is also found to be required by other activities. As new activities

are analyzed, fewer and fewer additional or unique equipment items are uncovered. The list of unique items of support equipment grows in a negatively accelerated fashion until after some point a plateau is reached and the analysis of additional activities leads to no major changes in the total inventory of support equipment required. As illustrated in Figure 3-20, this typical trend also has been observed in the present study. As may be seen from Figure 3-20, the initial activity considered required 12 items of support equipment. Each additional activity contributed only a few more items of support until after the 21st activity, no additional equipment items were added to the inventory and the commonality plot reached a plateau. A standard MDAC-McAuto curve-fitting program was used to develop the best fitting equation to describe this commonality curve. In this process, a number of equations were examined including those for a log-log linear curve, a true power curve, a linear curve fit, an asymptotic power function, a semilog-linear relation, a linear-semilog relation, an exponential curve, and

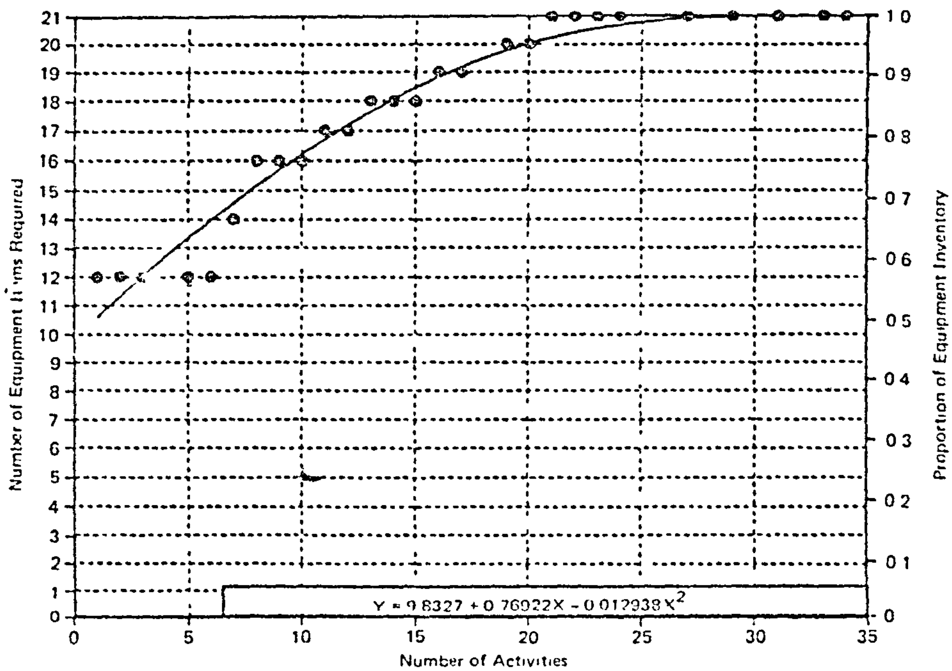

Figure 3 20. Equipment Commonality Supervised and Independent Modes

a quadratic curve. Of these, the best fitting curve describing the study data was found to be a quadratic equation in the following form:

$$Y = 9.8327 + 0.76922X - 0.012938X^2$$

where Y is the number of equipment items required, and X is the number of activities required in the mission. The coefficient of determination for this relationship (R^2) was 0.96293.

Recognizing the fact that most operational sequences to accomplish mission objectives require a number of different activities and recognizing that many individual support items would be common to more than one activity, it was believed to be desirable to include the commonality factor and to compare the relative cost of performing a given activity in each of the man-machine modes (manual, supported, augmented, teleoperated, supervised, or independent) as a function of the number of different activities required as well as by the number of times each activity is to be repeated during the operational sequence.

If it is assumed that there is a direct relationship between the implementation cost for accomplishing a specific activity and the number of supporting equipment items required (i.e., the Activity Implementation Cost is a function of the number of equipment items required), then a cost correction factor to allow for the commonality of equipment needs among multiple activities can be established as follows:

$$\begin{bmatrix}\text{COMMONALITY}\\ \text{COST}\\ \text{CORRECTION}\\ \text{FACTOR}\end{bmatrix} = \left[\frac{\text{IMPLEMENTATION COSTS FOR "N" ACTIVITIES}}{\text{IMPLEMENTATION COSTS FOR A SINGLE ACTIVITY}}\right]$$

$$= \frac{f\begin{bmatrix}\text{NUMBER OF EQUIPMENT}\\ \text{ITEMS REQUIRED FOR}\\ \text{"N" ACTIVITIES}\end{bmatrix}}{f\begin{bmatrix}\text{NUMBER OF EQUIPMENT}\\ \text{ITEMS REQUIRED FOR}\\ \text{A SINGLE ACTIVITY}\end{bmatrix}}$$

or

$$\begin{bmatrix}\text{COMMONALITY}\\ \text{COST CORRECTION}\\ \text{FACTOR FOR}\\ \text{MULTIPLE ACTIVITIES}\end{bmatrix} = \frac{9.8327 + 0.76922A_N - 0.012938A_N{}^2}{9.8327 + 0.76922A_1 - 0.012938A_1{}^2}$$

$$\begin{bmatrix}\text{COMMONALITY COST}\\ \text{CORRECTIVE FACTOR}\end{bmatrix} = \frac{9.8327 + 0.7922A_N - 0.012938A_N{}^2}{10.59}$$

Table 3-16 lists typical values of the Commonality Cost Correction Factor as a function of the number of activities required in the operational sequence.

A relationship can then be established to compare the cost effectiveness of alternative man-machine modes by taking the data on the estimated costs of performing a specific activity for any number of repetitions in each man-machine mode, as described in Section 3.4, and applying the following assumptions: (1) The cost for performing multiple activities in the man-machine modes requiring direct manual involvement (manual, supported, augmented, teleoperated) is directly proportional to the number of different activities required, and (2) the cost for performing multiple activities in the man-machine modes requiring indirect manned involvement (Supervised and Independent) can be described by a quadratic relationship as illustrated in Figure 3-20.

The expression presented as Equation One above can be modified to include the commonality factor and the locus of points describing the boundary where it is equally cost effective to implement the activity requirements by either of two man-machine modes can be determined as follows:

$$\begin{bmatrix}\text{COST FOR PERFORMING}\\ \text{AN ACTIVITY "N" TIMES}\\ \text{IN THE DIRECT MANUAL}\\ \text{MODE}\end{bmatrix} \times \begin{bmatrix}\text{NUMBER OF}\\ \text{DIFFERENT}\\ \text{ACTIVITIES}\\ \end{bmatrix} = \begin{bmatrix}\text{COST FOR PERFORMING}\\ \text{AN ACTIVITY "N"}\\ \text{TIMES IN AN INDIRECT}\\ \text{MODE}\end{bmatrix} \times \begin{bmatrix}\text{COMMONALITY}\\ \text{CORRECTION}\\ \text{FACTOR FOR}\\ \text{MULTIPLE ACTIVITIES}\end{bmatrix}$$

The Commonality Correction Factor is equal to: $\dfrac{9.8327 + 0.76922A_N - 0.012938A_N{}^2}{10.59}$

Table 3-16
COMMONALITY COST CORRECTION FACTORS

Number of Activities	Commonality Cost Correction Factor	Relative Cost/Activity
1	1.00	1.00
2	1.07	.54
3	1.14	.38
4	1.21	.30
5	1.27	.25
6	1.33	.22
7	1.39	.20
8	1.45	.18
9	1.50	.17
10	1.55	.16
11	1.60	.15
12	1.65	.14
13	1.69	.13
14	1.74	.12
15	1.78	.12
16	1.81	.11
17	1.85	.11
18	1.88	.10
19	1.91	.10
20	1.94	.10
21	1.96	.09
22	1.98	.09
23	2.00	.09
24	2.02	.08
25	2.04	.08
30	2.07	.07
35	2.07	.06

where A_N represents the number of different activities. It should be cautioned that the basic quadratic equation was derived from the data obtained in the current study and should be used only within that frame of reference. If the number of activities should significantly change, the optimal descriptive equation should be reestablished based upon a new set of limiting values.

Using this approach, equal cost curves for the manual mode compared to each of the other man-machine implementation modes were plotted for each activity as illustrated in Figure 3-21. When considered individually, each of these curves represents the locus of equal cost points for various combinations of the total number of unique activities required and the number of repetitions anticipated for a specific activity. Above or to the right of specific curves, it is more cost effective to use the man-machine mode noted and below or to the left of a specific curve, it is more cost effective to consider the use of a manual mode.

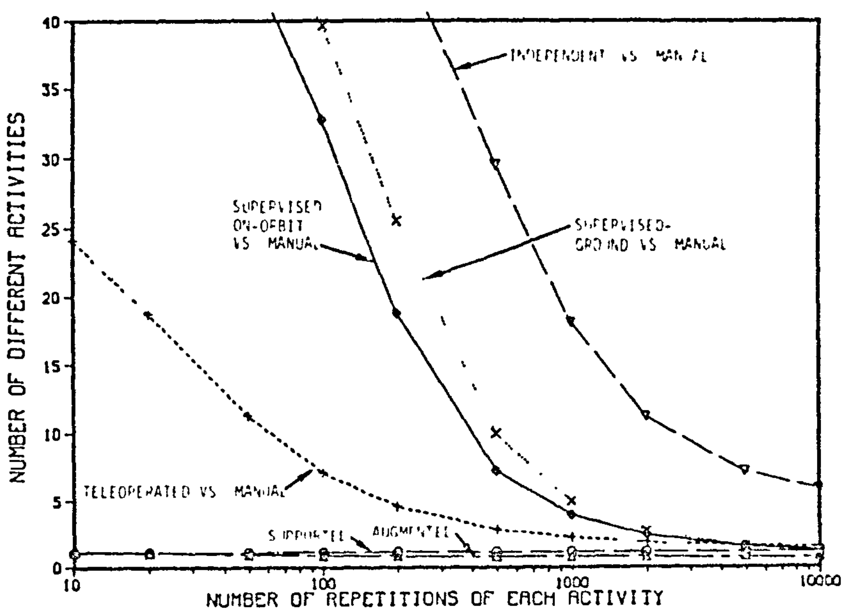

Figure 3-21. Equal Cost Curves for Manual Activation as Compared to Each of the Other Man-Machine Implementation Modes. Activity 29 -- Release/Secure Mechanical Interface.

When all of the individual curves are plotted together as a family, the areas bounded by the individual curves define the regions where each specific man-machine mode is the most cost effective. Figure 3-22 portrays these regions of applicability. As illustrated in Figure 3-22, if only the one activity were required to be performed, it would need to be repeated thousands of times before it would be cost effective to provide some degree of automated support (i.e., the supervised mode of operation). On the other hand, if a total of 16 activities were required to be performed to accomplish the mission objective, and if the number of times Activity 29 was to be performed were only two hundred, designing the mission objective to be accomplished in the supervised mode becomes an attractive option.

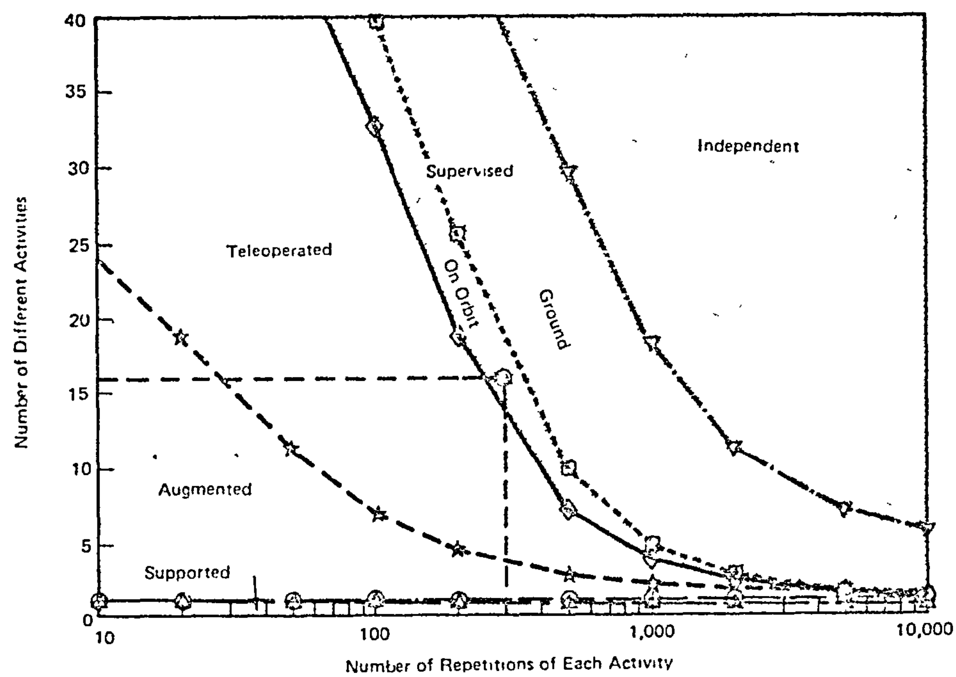

Figure 3-22 Activity Number 29 Release/Secure Mechanical Interface

From these graphic presentations of the equal cost curves, it can be concluded that if each man-machine mode is equally capable of meeting the performance requirements of a group of activities, it generally is more cost effective to implement the activity in one of the direct manual modes

(including supported or augmented) than in an indirect mode (supervised or independent). It is only when a series of 30 or more different activities is required to be repeated hundreds of times each, that the indirect modes of operation become the more cost effective modes.

Section 4
TECHNOLOGY REQUIREMENTS AND TASKS - TASK 3

The objectives of this task were to (1) identify the requirements for technology developments needed to enable and enhance the human role in space activities, and (2) uncover gaps that may exist in current technology development plans that will need to be filled to realize the full operational potential of advanced manned space systems.

Enabling technology development can be described as those specific developments necessary to provide the basic capability required to meet specific mission goals and objectives. Enhancing technology describes those research and development projects that are supportive of the major enabling technologies. The enhancing technological developments generally lead to standardization and improvements in productivity including performance, cost effectiveness and risk reduction.

A review of NASA planning documents has led to the conclusion that the current plans which NASA is in the process of developing and executing in support of the enabling technologies for future space programs do include the major issues of concern. No "show stoppers" were found that would preclude the development of a manned space platform capable of supporting the needs and objectives of a broad spectrum of future missions. On the other hand, a number of areas, which might be termed "enhancing technology," were identified where gaps in support exist and where supported research and development activities could greatly enhance the accomplishment of a wide range of missions in a more cost effective manner.

4.1 TECHNOLOGY REQUIREMENTS

In the identification of requirements for the technological developments that enable and enhance the human role in future space operations, four sources of information were utilized. These were as follows:

A. NASA Space Systems Technology Model - 5th issue, January 1984.

B. Research and Technology Objectives and Plans (RTOPS), 1983-84, as available from NASA Centers.

C. NASA Space Station Task Force Mission Requirement Working Group (MRWG) Model of the potential Space Station missions for the years 1991-2000.

D. The 37 generic activities defined in Task 2 of the THURIS study.

Source A provided an organizational framework for technology planning, source B provided the list of the research and technology objectives which are currently scheduled to be addressed, source C provided a time reference for determining when specific operational capabilities were needed, and source D defined the specific man-machine activities that will be required in accomplishing the operational objectives defined in source C. By considering each of these references in relationship to the others, it becomes possible to surface those activities most in demand and to assess the timeliness of NASA's planned and ongoing R&D projects as well as to identify areas of R&D coverage that may currently appear to be inadequate to support the Space Station related missions of the 1991-2000 time period, either in scope or in technical focus.

The first source of information examined was the NASA Space Systems Technology Model.(1) This seven-volume document represents a vital element of the nation's space technology program planning and implementation process and is a companion to the NASA Long-Range Planning Document. It is updated annually. Although the Space Systems Technology model covers all technical areas, the areas of specific interest to the THURIS study were those dealing with the human factors elements of manned systems.

Three types of human factors operations are described in the Space Systems Technology Model. The first class of operations includes "hands-on" tasks performed at crew stations located within the habitable portions of the manned space facilities. Technology needs of these work stations include displays,

(1) NASA Space Systems Technology Model, Fifth Issue dated January 1984. NASA-Office of Aeronautics and Space Technology, Code RS, Washington, D.C. 20546. Issued under the authority of Stan R. Sadin, Deputy Director, Program Development, OART/RS.

software advances, and man/machine task allocations. The crew work station needs include designs employing emerging display and control technology, "user friendly" interfaces, artificial intelligence, computer-aided problem solving, and assistance to the crew in decision-making activities.

The second type of human factors operations is "hands-on" tasks performed by the crew during extravehicular activities. Here the enabling technology requirements address "next generation" EVA work systems, improved tools, transfer aids and procedures. Typical products of these technologies include, low-fatigue/long-duration space suits, gloves and accessories, force-aided tools and fixtures, restraints and mobility aids, and situation and work status displays.

The third type of human factors operations is joint man-machine teleoperations, and includes technology focusing on the operator's work station, interface equipment and end-effector/actuator units. Elements of the work station include controls, operational displays, status monitoring displays, and control-display dynamics. Interface equipment issues include transmission of signals between operator and effector. The remote end-effector/actuator issues address sensing, manipulating, and mobility at the remote site. An overall issue is developing the technology which enables the extension of the human motor and sensory presence including both the psychomotor and the human intellect. A few examples of teleoperations applications include shuttle-attached manipulators, free-flying satellite servicing units, and automatic assembly machines.

The second source of information examined by the THURIS study team was those current Research and Technology Objectives and Plans (RTOPs) available as of April 1984 from the NASA centers that considered human factors enabling technologies. These RTOPs were arranged into the three types of operational considerations identified from the Space Systems Technology Model (Source No. 1); i.e., (1) crew station design, (2) extravehicular activity, and (3) teleoperations. The projected status of the outputs of these research areas was quantified in terms of the level of technology readiness expected from each project between the present time and the IOC of a Space Station

(approximately 1991). The readiness levels are defined on a seven-point scale as shown in Table 4-1. A list of the projects, their assigned NASA lead center, and their projected status is shown in Tables 4-2, 4-3, and 4-4, and further summarized on Figure 4-1.

The third source of information examined by the THURIS study team was the currently evolving space mission descriptive data being generated for the

Table 4-1 Technology Readiness Levels

LEVEL 1	BASIC PRINCIPLES OBSERVED AND REPORTED
LEVEL 2	CONCEPTUAL DESIGN FORMULATED
LEVEL 3	CONCEPTUAL DESIGN TESTED ANALYTICALLY OR EXPERIMENTALLY
LEVEL 4	CRITICAL FUNCTION/CHARACTERISTIC DEMONSTRATION
LEVEL 5	COMPONENT/BREADBOARD TESTED IN RELEVANT ENVIRONMENT
LEVEL 6	PROTOTYPE/ENGINEERING MODEL TESTED IN RELEVANT ENVIRONMENT
LEVEL 7	ENGINEERING MODEL TESTED SPACE
LEVEL 8	FULL OPERATIONAL CAPABILITY (FOC) (BASELINED INTO PRODUCTION DESIGN - LEVEL 8)

Table 4-2. Crew Station Design Related Projects and Status

PROJECT	TECHNOLOGICAL READINESS LEVEL (1-7)	& DATE PROJECTION
- ADVANCED INFORMATION PROCESSING SYSTEM	(6)	MAR 86
FLIGHT DEMONSTRATION (AIPS) - JSC	(7)	DEC 88
- MICROPROCESSOR CONTROLLED MECHANISMS - JSC	(3)	AUG 87
- AUTOMATED SUBSYSTEM MANAGEMENT - JSC	(5)	DEC 85
- CREW STATION HUMAN FACTORS - JSC	(3)	FEB 86
- SPACE STATION DATA MANAGEMENT SYSTEM - JSC/GSFC	(3)	JUN 85
- MAN'S ROLE IN SPACE MAINTENANCE - MSFC	(7)	OCT 86
- MAN/MACHINE INTERFACE DESIGN TECHNOLOGY - MSFC	(6)	APR 85
- HABITABILITY TECHNOLOGY - MSFC (APPLICATION OF THURIS RESULTS)	(3)	SEP 86
- INTERACTIVE HUMAN FACTORS (TDMX 2470) - MSFC	(7)	JULY 1991
- EARTH OBSERVATION INSTRUMENT TECHNOLOGY (TDMX 2260) - LRC	(7)	JULY 1992
- HABITATION TECHNOLOGY (TDMX 2520)	(7)	JULY 1991

Table 4-3. Extravehicular Activity Related Projects and Status

	TECHNOLOGICAL READINESS LEVEL (1-7) & DATE PROJECTION	
- LASER ANTHROPOMETRIC MAPPING SYSTEM - JSC	(4)	DEC 86
- GLOVE END EFFECTOR - JSC	(5)	FEB 86
- EVA GENERIC WORK STATION AND RESTRAINTS - JSC	(6)	DEC 86
- EMU HEADS UP DISPLAY - JSC	(5)	JUN 85
- HUMAN STRENGTH AND MOTION MODEL - JSC	(5)	MAY 87
- STRUCTURAL ASSEMBLY DEMONSTRATION EXPERIMENT - MSFC	(7)	JUL 85
- MODULAR CONSTRUCTION/MANIPULATOR SERVICING - MSFC	(6)	MAR 87
- ORBITAL EQUIPMENT TRANSFER TECHNIQUES - MSFC	(1)	NOV 86
- DEPLOYMENT/ASSEMBLY/CONSTRUCTION (TDMX 2060) - LRC	(7)	JULY 1992
- LARGE SPACE ANTENNA TECHNOLOGY (TDMX 2210) - JPL	(7)	JULY 1992

Table 4-4. Teleoperations Related Projects and Status

	TECHNOLOGICAL READINESS LEVEL (1-7) & DATE PROJECTION	
- LEO PLATFORM/REMOTE SERVICING - MSFC	(5)	DEC 86
- SPACE PLATFORM EXPENDABLES RESUPPLY - MSFC	(7)	APR 88
- SATELLITE AND SYSTEMS SERVICING - MSFC	(6)	JAN 87
- TELEPRESENCE WORK STATION - MSFC	(6)	JUL 87
- ADVANCED ORBITAL SERVICING TECHNOLOGY EXPERIMENTS - MSFC	(7)	AUG 86
- TELEPRESENCE TECHNOLOGY (TDMX 2460) - JPL	(7)	JUL 1993
- SATELLITE SERVICING TECHNOLOGY (TDMX 2560) - MSFC	(7)	JUL 1991
- ATV SERVICING TECHNOLOGY (TDMX 2570)	(7)	JUL 1991

Space Station Mission Requirements Working Group (MRWG) Mission Model. The MRWG is the part of the Space Station Task Force assigned the responsibility for defining a model mission, schedule, and set of requirements for the 1991-2000 time frame. Within the model at the present time are seven technology development missions directly associated with human factors enabling technologies. These missions are also included on Tables 4-2, 4-3, and 4-4, and are identified by the TDMX designator in parentheses following the project title.

The 37 generic activities defined in Task 2 of the THURIS study were correlated with space station crew task assignments involving 16 mission

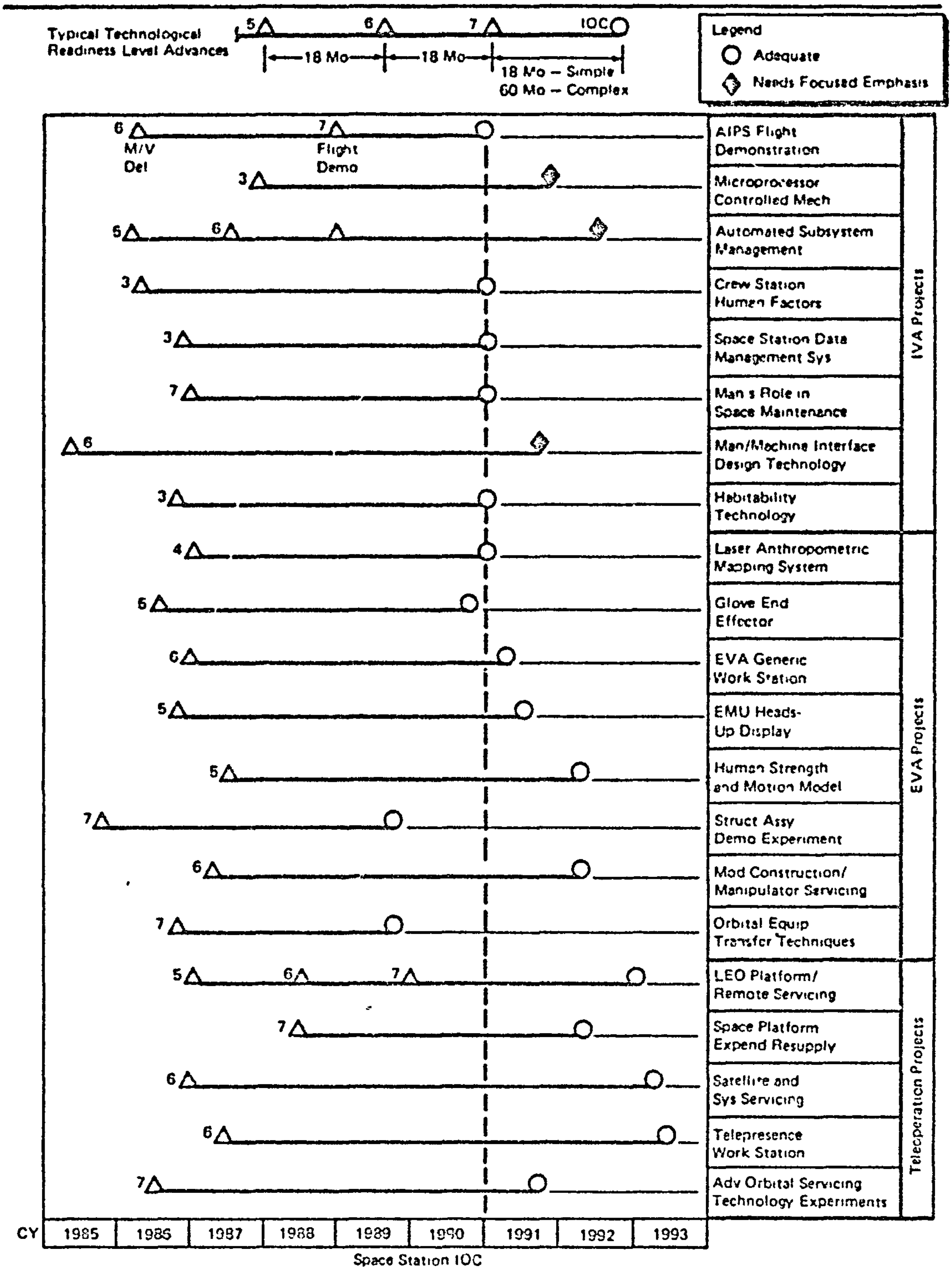

Figure 4-1. Supporting Human Factors Enabling Technology

parameters. These parameters included (1) the location of the work (IVA, EVA); (2) the involvement of the crew with the mission equipment (e.g., initial setup and checkout, daily routine operations, periodic operations less frequent than daily mission equipment maintenance, repair operations, and response to change and unexpected events); and (3) the places where the work is performed relative to eight space station functional elements. These space station functional elements include pressurized modules, attached payloads in unpressurized areas, command, control, and communications (C^3) functions, deployment/construction/assembly functions, proximity operations, and payload staging for earth return. The descriptions of the functional elements defined by the MRWG are summarized in Table 4-5.

The results of correlating the generic activities to the space station mission parameters are displayed in Figure 4-2. An entry in the body of the matrix indicates that for a particular crew activity and mission parameter intersection, a mission-related need is established. Inspection of the number of mission parameters associated with each of the activities shows that while all activities are required in various locations to support future missions, 11 out of the 37 activities are in most demand. These eleven activities (indicated by a count of 15 or 16 in the total column of the matrix) include: adjust/align elements; communicate information; confirm/verify procedures/schedules/operations; gather/replace tools/equipment; implement procedures/schedules; inspect/observe; position module; problem solving/decision making; release/secure mechanical interface; transport loaded; and transport unloaded.

4.2 TECHNOLOGY GAPS

Technology gaps can arise from one factor or a combination of three factors: (1) need for increased performance capability, (2) schedule incompatibilities, and (3) costs associated with (1) and (2).

A gap in technology can exist either when the capability to perform a certain action is totally lacking or when the capability to perform a given action is questionable and associated with a risk factor which is unacceptable.

Table 4-5
MANNED STATION ELEMENT FUNCTIONS

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1. Pressurized Laboratory
A pressurized crew station module will provide power, low gravity, and long duration crew support for conducting laboratory work and operational support. Payload elements may be integrated directly into the module.

2. Attached Payloads
Provision will be made to accommodate payload elements exterior to the pressurized module. Limited resources plus periodic crew tending and servicing will be provided. Resources could include command, control, and data handling.

3. Command, Control, and Communications Support
Provisions will be made within the space station system to remotely command, control, monitor, throughput, and preprocess data for free-flyers and platforms.

4. Deployment, Assembly, Construction
The space station system will provide support capability for construction, assembly, and deployment. This support implies all required service devices such as manipulators and MMUs.

5. Proximity Operations
Payloads capable of maneuvering themselves within a reasonable distance of the station will be maintained, serviced and checked out. Reasonable distance is defined as that limited by capability of EMU or a small proximity operations vehicle (POV).

6. Remote Maintenance, Servicing, Checkout, and Retrieval
Payloads, remote from the space station, can be maintained/serviced and checked out via a remotely operated service vehicle. Servicing could be provided on the payload at its locations or the payload could be retrieved, serviced, and returned. The space station likewise provides for commanding, controlling, maintaining, and servicing the service vehicle.

7. Payload Integration and Launch
Payloads/satellites requiring transfer to other orbits can be brought to the space station by the Shuttle Orbiter, integrated with a transfer stage, and launched. The transfer stages could be commanded and controlled from the space station. These stages could be either expendable or reusable. Reusable transfer stages can be based at the space station, serviced, maintained, and refueled. Expendable stages could be stored and serviced.

8. Payload Staging for Earth Return
Payloads, experimental samples, or captured samples requiring return to earth can be demated, prepared and stored until placed in the Orbiter for return to earth. This function also includes the preparation of payload equipment for return at the conclusion of its mission.

GENERIC ACTIVITIES	Space Station Mission Parameters																
	Location		Crew Activities						Space Station Functional Elements								
	IVA	EVA	Initial Setup	Daily Activities	Periodic Activities	Maintenance	Repair	Respond to Change	1 Press Module	2 Attached Payload	3 C^3	4 Deploy/Constr	5 Prox/Ops	6 Remote Ops	7 Payload Integ	8 Staging/Return	Totals
1 Activate/Initiate System Operation	X	X	X		X	X	X	X	X	X	X		X	X			12
2 Adjust/Align Elements	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	16
3 Allocate/Assign/Distribute	X	X	X	X	X	X	X	X	X	X	X			X		X	13
4 Apply/Remove Biomedical Sensor	X		X	X	X				X								5
5 Communicate Information	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	16
6 Compensatory Tracking	X			X	X			X	X	X	X			X			8
7 Compute Data	X			X	X	X		X	X		X						7
8 Confirm/Verify Procedures/Schedules/Operations	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	16
9 Connect/Disconnect Electrical Interface	X	X	X			X	X	X	X	X	X		X	X	X	X	13
10 Connect/Disconnect Fluid Interface	X	X	X			X	X	X	X	X	X		X	X		X	12
11 Correlate Data	X			X	X	X	X		X		X						7
12 Deactivate/Terminate System Operation	X	X			X	X	X	X	X	X	X		X	X			11
13 Decode/Code Data	X			X	X				X		X						5
14 Define Procedures/Schedules/Operations	X				X	X	X	X	X		X						7
15 Deploy/Retract Appendage		X	X		X	X	X	X	X	X	X	X		X	X	X	13
16 Detect Change in State or Condition	X	X		X	X	X	X	X	X	X	X			X	X		12
17 Display Data	X		X	X	X	X		X	X		X	X		X	X		11
18 Gather/Replace Tools/Equipment	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	15
19 Handle/Inspect/Examine Live Organisms	X		X	X	X				X								5
20 Implement Procedures/Schedules	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	16
21 Information Processing	X	X		X	X			X	X	X	X		X	X		X	11
22 Inspect/Observe	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		15
23 Measure (Scale) Physical Dimensions	X	X		X	X		X	X	X	X				X			9
24 Plot Data	X			X	X	X			X		X						6
25 Position Module	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	16
26 Precision Manipulation of Objects	X	X	X	X	X	X	X	X	X	X		X	X				12
27 Problem Solving/Decision Making/Data Analysis	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	15
28 Pursuit Tracking	X	X		X	X				X	X	X			X			8
29 Release/Secure Mechanical Interface	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	16
30 Remove Module	X	X		X	X	X	X	X	X	X	X		X	X	X		13
31 Remove/Replace Covering	X	X		X	X	X	X	X	X	X	X	X	X	X			13
32 Replace/Clean Surface Coating	X	X			X	X	X	X	X	X							8
33 Replenish Materials	X	X	X	X	X	X	X	X	X	X	X						11
34 Store/Record Element	X	X		X	X	X	X	X	X	X	X			X	X	X	13
35 Surgical Manipulations	X			X	X			X	X								6
36 Transport Loaded	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	16
37 Transport Unloaded	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	15

Figure 4-2. Correlation of Generic Activities and Space Station Mission Parameters

A gap in tecnnology can be identified if the technology readiness level does not meet schedule constraints for implementation.

A gap in technology can also arise when the costs associated with establishing the capability to perform an action at a specific time in the future puts the specific action outside of the limits of economical viability. Often these cost factors can be the predominant drivers in determining the feasibility of a given technological approach. For example, the technology exists to produce flawless gem-quality diamonds of very large size. The cost of this production, however, is such that the synthetically produced end product would be priced above the present market for natural diamonds with equivalent characteristics.

One of the more important indicators of the level of technology risk is the time required to progress from one level of technical readiness to the next until ultimately fully operational capability (FOC) is achieved. Typically the period of time to progress from level 2 to FOC ranges from eight to twelve years, depending on the complexity of the element being developed. The readiness levels leading to FOC are noted on Figure 4-1 for each of the enabling technologies currently included in NASA Research and Technology Objectives and Plans and for which a full-scale development is the ultimate objective. As a general observation, those projects associated with EVA and teleoperations reach FOC fruition in a time domain consistent with the IOC of the space station. Hence, activities depending upon the successful completion of these projects can be accomplished with a reasonable and acceptable level of technical risk. For the IVA work station related projects, however, the risk assessment acceptability is less clear.

To illustrate the complexity to be anticipated in the design of IVA work stations, consider the Advanced Solar Observatory. The Advanced Solar Observatory (ASO) mission is one of the more complex of the missions described in the MRWG data set. The payload equipment includes the solar soft x-ray telescope, the pinhole occulter, and the solar optical telescope. Assigned to be accommodated by the 28-1/2-degree co-orbiting platform, the payload will be periodically maintained and refurbished by a station-based remote servicer. As an option, the payload could also be accommodated as a free flyer or as a

space station attached payload. Other options being evaluated include final assembly and checkout at the station prior to placement in operational orbit.

The two station crewmembers assigned to the mission will need to be specially trained and will operate 8 hours each day. The crew will view three video displays at an IVA work station for real time operation of the mission. In order to enable and enhance the scientific objectives of the mission, the design of the crew work station which supports this mission needs to be efficient from an operator's point of view, user friendly from a man-machine intellectual interchange point of view, and "expert" from an information sharing and data recall and exchange point of view.

The Advanced Solar Observatory illustrates a key point. As the sophistication of future payloads increases, there will be an accompanying shift in crew support skills/requirements. A transition occurs from the more physical tasks to the more intellectually oriented work activities with the progression of time. This pattern appears to be analogous to the industrial development dynamic wherein the blue collar worker changes to a white collar worker as the transition from production of goods to provision of services takes place.

An MRWG mission even more complex than the ASO is the Solar Terrestrial Observatory (STO). As defined by the MRWG, this mission is planned for a first flight in the 1991-1992 time frame with a mission duration of 730 days. The STO mission calls for operations of 90 days per year or about one week each month. The general objectives of the mission are to study space plasma atmospheric interactions utilizing observations of natural and induced atmospheric emissions ~~and~~ to exploit the natural plasma laboratory of space. The specific objectives are to investigate the influence of an electron beam, an arc jet, and a neutral gas plume on the high-altitude atmosphere, including the production of artificial aurora. In addition, radio waves are transmitted from the payload in the HF and VLF bands and received in the HF band. Atmospheric effects in the visible and UV are to be observed with a video camera. Solar monitoring instruments are also planned to be included, as well as an x-ray telescope.

In order to appreciate the complexity of the STO mission, it is appropriate to describe the elements of the payload. The objectives are met by an electron beam of energy 1 to 20 kev with 1 to 25 kilowatts of power, a helium or argon magneto-plasma-dynamic arc-jet with 2 to 10 kilograms per pulse, 250 ev particle energies, a charge current probe from the OSS-T satellite, and possibly a neutral gas plume. This collection of science instruments is called SEPAC, (Space Experiment with Particle Accelerators). The electron beam accelerator (EBA) will be designed for ultimate power levels of some hundred kilowatts, allowing for substantial growth in objectives. The power radiating radio frequency facility is called WISP (Waves in Space Plasma) and consists of a VLF transmitter operating in the 1 to 30 kilohertz band, an HF transmitter, and a receiver operating from 0.1 to 30 megahertz. The dipole antenna subsystem radiates VLF and HF and receives the HF signals. Antenna elements extend 150 meters in each of two opposite directions with tip-to-tip distance of 300 meters. The common operating research equipment assembly controls antenna retraction and extension.

The complete payload package includes the SEPAC, WISP, and AEPI (video camera) instruments together with a Solar Monitor package and the x-ray telescope. Subsatellites and instrument probes are also required. The payload is visualized as being contained on one or more pallets which include the science instruments, an antenna support structure, and a berthing adapter assembly for attachment to the Space Station. Integration hardware for providing power, thermal control, signal transfer, and electrical distribution is assembled on the pallet(s). The integration hardware includes an active thermal loop.

The baseline scenario calls for one week per month of intensive operation of SEPAC and WISP with the assumption that one (SEPAC or WISP) is in a passive mode while the other is active. Coordinated (interleaved) pulses of SEPAC and WISP would be desirable. A growth option includes operation of SEPAC and WISP at the same time if resources permit. The video camera is included to observe the effects of SEPAC and WISP, primarily. It is required for all SEPAC operations and some WISP operations. The camera is normally pointed along the magnetic field toward any auroral spot formed by emission from the SEPAC and/or WISP units. The camera is to controlled by the Space Station crew.

An operator's console within the pressurized elements of the Space Station is visualized as being used to monitor health and safety of the mission equipment, to provide quick-look data reduction, and to issue commands. Support equipment for SEPAC and WISP is to be mounted at the crew work station in addition to the control electronics for these instruments and for the SUSIM, the x-ray telescope, and the AEPI. Displays are to provide output data including the video results from AEPI. The operator's console will also be used to control instrumented sub-satellites. Crucial to the success of the mission will be the efficiency of the crew/mission equipment functional and operational interfaces as embodied in the selection and implementation of the design features of the work station.

As the emphasis changes in the workplace, as illustrated by the ASO and the STO missions, the design of the crew work stations must also change to reflect the change from the physical to the intellectual. To more effectively utilize human intelligence, a better match is required with machine intelligence and with "expert" systems. Activities important in IVA for these advanced missions are Adjust/Align, Communicate Information, Confirm/Verify, Implement Procedures, Inspect/Observe and Problem Solving/Decision Making/Data Analysis.

The successful implementation of the MRWG Advanced Solar Observatory and Solar Terrestrial Observatory missions will be highly dependent upon the development of work stations that (1) communicate fluently with humans (speaking, writing, drawing, etc.); (2) assist in interactive problem solving and inference functions (deductive reasoning); and (3) provide knowledge base functions (information storage, retrieval, and "expert" systems for support). In order to develop these work stations of the future, however, a better understanding is required of human intellectual capabilities and how they function in different operations (such as convergent production, divergent production, memory, cognition, or evaluation) and with different contents (such as pictorial or figural, symbolic, semantic, and behavioral elements) in order to obtain specific products (implications, transformations, etc.). Even when people don't speak the same language they can communicate to some degree using gestures, facial expressions, etc., because they share common biological structure, needs, and common patterns of thought and behavior and knowledge of

the world. A need exists for a more "natural" language for man/machine communication using interfaces that are congenial and transparent for the average person. The use of voice interactive controls and displays offers considerable promise for enhancing man/machine communications.

With regard to the issue of technology readiness and risk assessment, the schedule of project accomplishments shown in Figure 4-1 suggests that the EVA enabling technologies appear to be adequately planned in order to support the space station scheduled IOC in 1991. This view is further supported by the fact that the EVA equipment, for the most part, is of the "carry-on" as opposed to the "built-in" character. Carry-on equipment items are more easily accommodated than are mission and payload equipment items which must be incorporated in the basic station design. For this reason carry-on items can be integrated into the station build-up sequence later in the life cycle than can mission and payload equipment items.

In contrast with the EVA technologies, the IVA technologies are an integral part of the basic design of the space station. At the outset, this would suggest that the IVA capabilities and work stations would need to be frozen in design several years before the start of the build-up and launch sequence for the station modules and elements. On the other hand, these work stations must be designed to be capable of meeting the needs of a continually changing set of mission requirements, some of which (for example, the ASO and the STO missions) will place an extremely complex set of operational demands on the control/display configurations of the work station. This scheduling consideration strongly suggests that a technological gap exists in the work station related projects and planning. It is further suggested that these IVA related technology developments need to be focused on designs which are adaptive and transparent to emerging design improvements, allowing for both hardware and software updates to be made to the basic work station even after the work station is operational.

The human being represents a remarkably flexible and adaptable system. The human can learn to operate and function effectively in many nonoptimal work environments. It has been said that system designers often utilize the human component in a man-machine system as a glue to hold the rest of the

system together. The real issue to consider in the development of work stations is to increase the productivity of the human in order to enhance his value to the mission. In order to increase human productivity we must continue to develop our understanding of the cognitive processes involved in work station design and we must continue the ~~development~~ of aids and techniques that can be used to enhance human productivity. Some of the specific issues related to work station design that fall in the domain of "enhancing" technology and can be considered as technology gaps at the present time are as follows:

A. Nature of Human Intelligence. Continuing effort should be directed toward developing a better understanding of the nature of human intelligence in order to develop work stations permitting more effective use of human intellectual capabilities.

By taking advantage of ongoing work in the behavioral sciences oriented toward developing paradigms of human intellectual processes and operations, the relationships of these processes to different contexts and to different products can be used to establish specific goals for technological developments to enhance the human role in space. Three areas of research and development should be emphasized:

1. Development of systems that communicate fluently with humans through speaking, writing, drawing, etc. Interfaces must be congenial and transparent for the average person.

2. Development of problem solving and inference functions utilizing automated classification techniques, multispectral image exploitation, and artificial intelligence applications for sensor data fusion. To date artificial intelligence has been of limited value in formulating optimal combinations of sensory data because specific combinations are based upon the needs and experiences of specific users.

3. Development of knowledge base functions or so called "expert" systems utilizing the efficient storage and selective retrieval of information. Much of the current work in the behavioral sciences is oriented toward examining the differences between experts and novices in activities such as playing chess, solving problems in physics, or in computer programming. The general finding is that most differences seem to be qualitative rather than quantitative, i.e., differences in approach rather than in the amount of processing or searching done. While processing roles

can be speeded up for novices, by replicating expert strategies, results to date suggest that we are a long way from being able to painlessly and instantly make a novice an expert in any given field.

B. Measurement of Human Productivity. Continuing effort is required to develop valid measures of human performance and productivity. The assessment and/or evaluation of human-machine systems is impossible without techniques to accurately measure human performance in the operational environment. Such measurement techniques are necessary to provide objective data that can be used to improve operational procedures and system design concepts. A problem especially common to human factors evaluations is that the measurement techniques proposed often modify, bias, or otherwise change the behavior being observed. The most pertinent way of avoiding this form of "instrumentation error" is to develop and validate performance measurement techniques that do not interfere with the behavior being observed. Techniques such as remote movement-sensing devices, voice stress analyzers, and other indirect or secondary behavioral measurements offer promise of providing noninterfering performance measurement capability. Before such techniques can be meaningfully employed in the operational environment, however, they need to be validated to ensure that they indeed measure what they are purported to measure. This will require laboratory and field studies under controlled conditions.

Another research area of considerable current interest and one that bears directly on the human role in future space systems is the area of "cognitive ergonomics" or mental workload assessment. While man's physiological performance limits are fairly well defined, his mental workload limits are less completely understood. It is known that excessive mental workload negatively affects human operators in both their physical and psychological well-being. The effect of stress on cognitive performance tends to manifest itself in a narrowing of the span of attention, inadequate distribution and switching of attention, forgetting of proper sequences of actions, incorrect evaluations of situations, slowness in arriving at decisions, and failure to carry out decisions made. Questions regarding the amount of stress a human operator can accept before performance deteriorates or breaks down need to be resolved, and measurement and predictive devices need to be developed. Mental workload should be one of the major criteria

upon which decisions covering the acceptability and effectiveness of man-machine systems are made.

Recent research on the use of (1) the P-300 evoked cortical (brain) response potential (ERP), and of (2) sinus arrhythmia as potential indicators of cognitive performance levels shows promising results.

These and other similar issues relating to the measurement of human performance bear directly on the technology requirements and planning for hardware and system design, and on the operational and procedural recommendations for augmenting and optimizing the human role in space.

C. Critical Incident Analysis of Human Performance. Continuing effort is required to investigate and understand the causes of the "human error" in space system operations as well as incidents of exceptional performance, in order to identify and classify the causal factors and to establish guidelines for the design of future space systems.

It is recognized that the capability for direct human intervention can enhance the reliability of advanced systems. However, precise mathematical modeling of human performance in the context of establishing the reliability of complex electromechanical systems is an elusive goal. A more logical approach is to focus on case studies of either exceptional behavior, or conversely on human error in performance, and to diagnose the factors contributing to the exceptional behavior, or conversely the causes of the errors. By better understanding the causes of human error and/or the factors leading to exceptional performance through the analysis of previous incidents, we can recommend procedures that permit the human to enhance system operations by reducing the risk of system failure.

D. Space Station Workshop. Continuing effort is required to develop the technology needed to provide an organized, integrated, on-orbit maintenance depot-workshop for the space station. This requires developing the tools and devices for use in zero-g as well as the integrated workshop concept. The tools include lathes, milling machines, grinders, welding machines, and work benches.

To date, on-orbit maintenance and repair has been limited and generally ad hoc. A permanent space station will require and provide the unique opportunity for extensive real-time orbital maintenance of the station itself, its ancillary systems, and various satellites. To support such a range of requirements, an on-orbit, maintenance depot-workshop technology must

be developed. Standardization of hardware cannot be guaranteed; therefore, the maintenance-servicing facility must be flexible in its capabilities, yet sufficiently organized to accommodate varied spacecraft functions. Special tools and techniques must be developed to complement the planned standard tool kit approach. Fabrication must be considered as a possibility. Large-vehicle restraint techniques, support lighting, and typical shop facilities (air, power fluids, etc.) must be considered.

E. Visual Display Development. Continuing effort is required in the development of visual display terminals since it is anticipated that just as today, 80% of the information required by future space crews will be obtained through the sense of sight. Whether video displays or other visual media are used, issues ~~to~~ be addressed include such items as the consideration of the following:

- Surface Screen Polarity and Color
- Surface Screen Reflections/Filters
- Display Positions
- Display Luminance
- Display Figure-Ground Contrast
- Character Design
- Information Content Formatting
- Flicker
- Ambient Illumination
- Types of Tasks
- Time Constraints for Utilization of Specific Visual Displays

4.3 TECHNOLOGY PLAN

NASA has recently instituted a human factors research program to ensure the timely availability of man-machine interface design technology for the space program. Past experience, as well as automation technology forecasts, point to a need for the human's unique capabilities in a maximally effective and efficient program to utilize and to exploit the potential of space. However, the high cost of each man-hour in space, the difficulty in handling injuries, and the adverse public sentiment that would result from mission failures require that humans in space be provided with maximally effective and safe tools, procedures, and work stations.

The goal of NASA's space human factors program is to develop the technology for (1) determining which tasks should be done by humans and which by automation; (2) determining which human tasks should be done in the shirtsleeve environment of the spacecraft and which in the EVA environment wearing spacesuits; and (3) development methods for designing safe, effective tools, procedures, and crew stations for astronaut use. The program to accomplish this is called manned systems and is divided into the following elements:

A. Basic Methodology
B. Crew Station Design
C. Ground Control/Operation
D. Teleoperations
E. Extravehicular Activity Support

Basic methodology encompasses the development of human factors techniques, methods, data bases, and standards to design and evaluate human/system interfaces for use in space anthropometry, methods for formatting support documentation, and methods for allocating tasks to humans and to automation.

Crew station design focuses on developing methods and techniques for using advanced display and control technology (e.g., flat panel displays, touch-sensitive panels, voice recognition/synthesis, etc.) more efficiently.

Ground control operation encompasses the development of techniques for designing ground control stations requiring few human controllers and solving the human implications of transferring operations (e.g., assembly, test, and launch) from the ground to a space station.

Teleoperations focuses on the development of man-machine interface requirements of teleoperators (remote manipulation devices). This includes visual and tactile feedback to the human, as well as information input methods.

Extravehicular activity support encompasses the development of improved tools, procedures, and work stations for the suited astronauts and the design of equipment for ease of servicing by extravehicular activity. NASA's current EVA system uses a "soft" spacesuit that operates with a pure oxygen atmosphere

at 4.2 pounds per square inch (psia) absolute pressure and a Portable Life Support System (PLSS) that uses LiOH cartridges for carbon dioxide removal, bottled oxygen at 6,000 psia for gas makeup, and a water boiler that vents about 2 pounds of water per hour for heat rejection.

A "hard" suit is now under development that can operate within an internal pressure of 8 psia and is expected to afford improved mobility and reliability. This suit is expected to eliminate the need for prebreathing oxygen to purge nitrogen from the wearer's body fluids before EVA operations. The most difficult problems are expected in development of a more compact PLSS that incorporates a regenerable carbon dioxide removal subsystem and provides thermal control without venting water.

As was described in Table 4-1, seven levels of technology readiness can be used to define the relative level of maturity of a given concept. The time scale required to achieve each level of technological readiness depends in large part upon the degree of complexity of the system to be developed. For relatively simple systems, the times required to move from level one to level seven may take from one to five years. This time range often reflects the impact of factors other than technical progress on the development process, such as political or budgeting constraints or the availability of corollary systems required to demonstrate or aid in the development of the item in question. An example of the development path for a simple system is illustrated in Figure 4-3. The devices in this case are small electrical connector tools to be used in changing orbital replacement units (ORUs) on a space platform. During neutral buoyancy tests at MSFC in 1981 the need for such tools was identified. The steps from conceptual design (level 2) to testing an engineering model (level 6) took about one year. To proceed to the next level of testing an engineering model in space and then to obtain full operational capability (FOC), approximately 30 months will be required because of scheduling and STS manifest constraints.

The time requirement to move from level one to level seven for a more complex system may take from 10 to 20 years. An example of the development path for a more complex system is illustrated in Figure 4-4. The system illustrated is an Electrophoretic Production Unit currently under development at McDonnell Douglas. Although the potential of electrophoresis as a

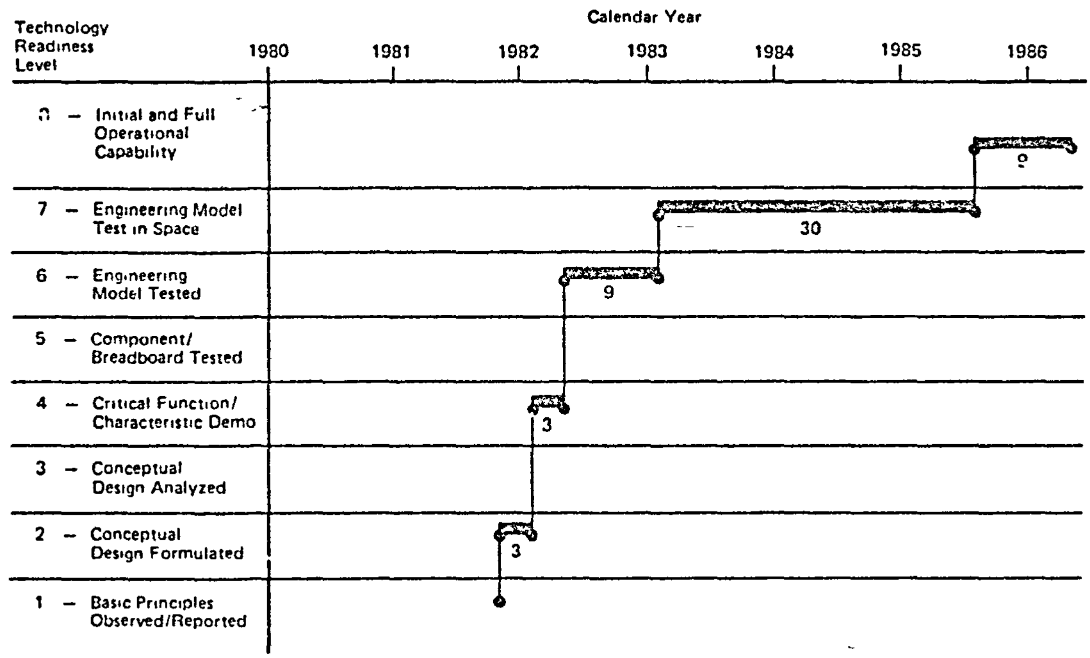

Figure 4 3. Development Path for Electrical Connector Tools

separation technique has been known since the turn of the century, the specific application and value of a space-based system was initially conceived in the period between 1972 and 1974. By 1975 a conceptual design (level 2) had been developed and engineering models were developed and tested (level 6) in the 1979-81 time period. The first test of the engineering model in space occurred on STS-4 in June of 1982. Tests will continue through 1984. The development of a full-scale production facility in all probability will depend upon the availability of a manned space station with a current estimate of FOC in 1992. Similar examples of the time required for technological advancement can be drawn from the historic data of other complex space systems. The concept of building and launching a diffraction limited IR-VIS-UV orbiting telescope was advanced in the early 1960s. Over 20 years will have elapsed between the early conceptual design (level 2) and the achievement of full operational capability of the space telescope in 1986.

This composite experience is summarized in Figure 4-5. This experience when related to the space station development schedule and to the technology

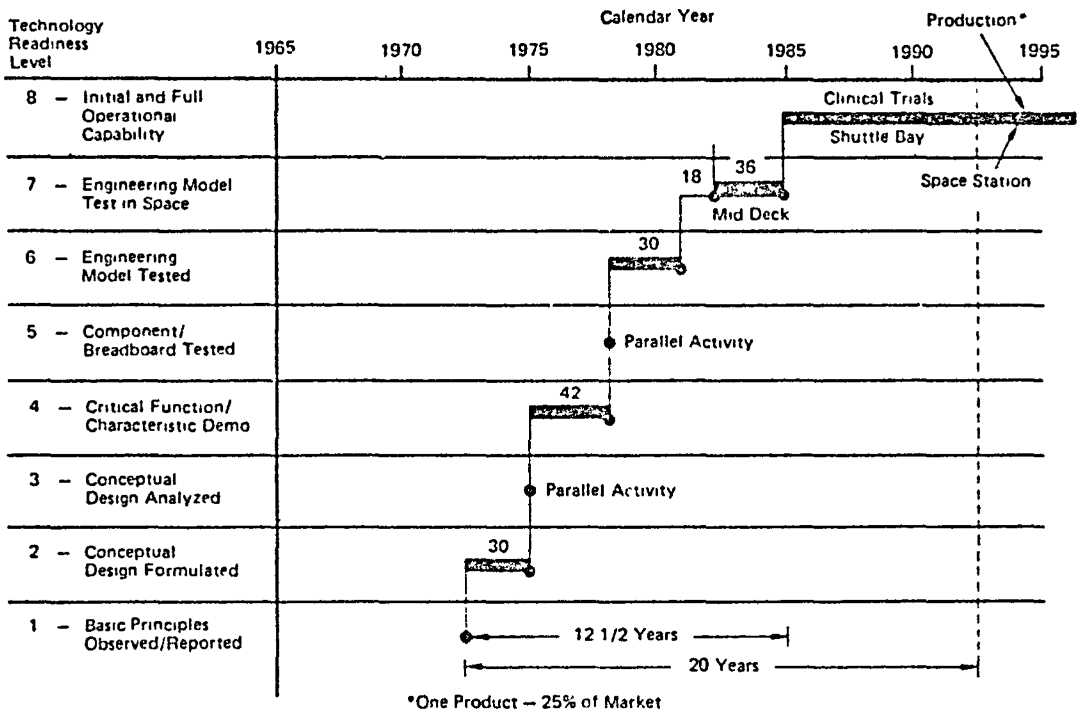

Figure 4-4. Development Path for Space Based Electrophoretic Production Units

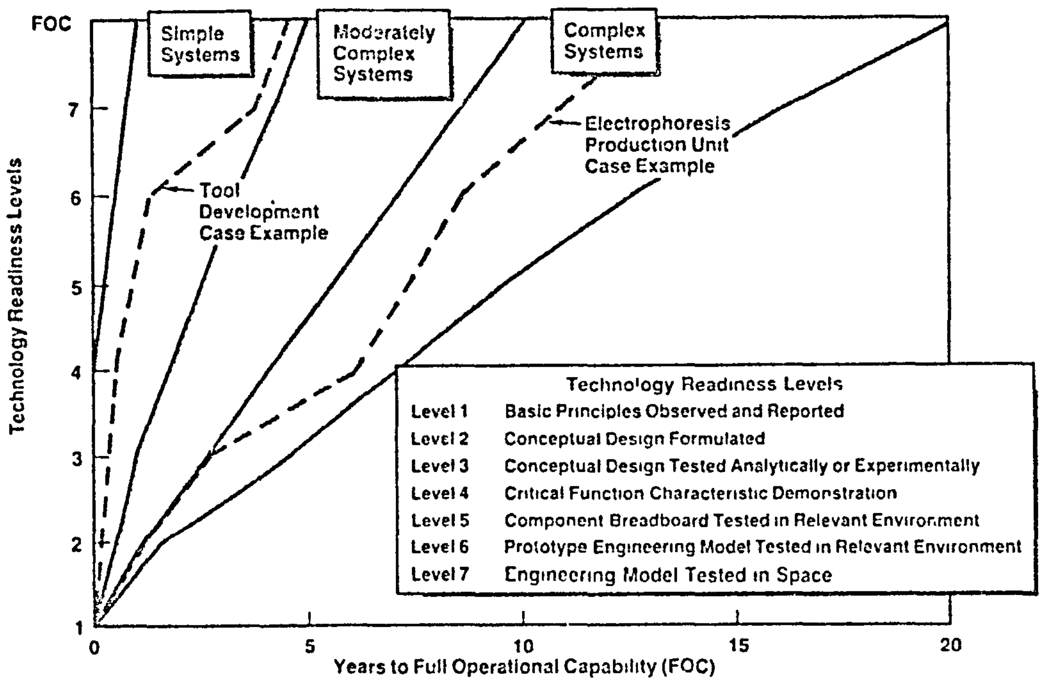

Figure 4-5. Technology Advancement Classifications

gaps identified in Section 4.2 provides a frame of reference for creating a technology plan for advancing the human role in space.

Using NASA's human factors research program as a guide, issues dealing with Basic Methodology can be considered to reflect a technology readiness level of one. Issues dealing with Crew Station Design reflect a technology readiness level of two. Issues dealing with Ground Control/Operation reflect a technology readiness level of three. Current Teleoperations research and development programs also reflect a technology readiness level of three. Extravehicular Activity Support programs are currently quite far along and could be considered to be at level four or level five.

In Figure 4-6, estimated time-phased technology readiness levels of the five areas which were identified in the THURIS study as representing developments needed for the enhancement of crew work station designs are plotted to show their relationship to the Space Station Reference Schedule and the current NASA Human Factors Research Program categories.

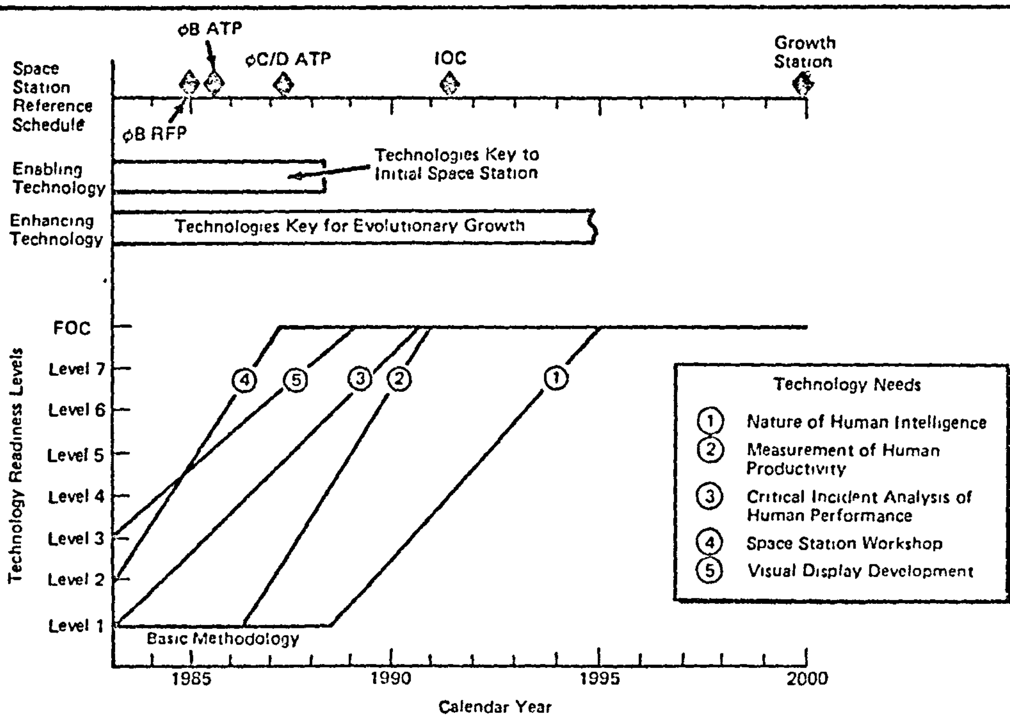

Figure 4-6. A Time-Phased Technology Plan for Critical Areas of Enhancing Technology

Figure 4-6 suggests the recommended timetable for implementing systematic studies of these research areas including ground (levels 1 to 4) and flight (levels 5 to 7) experiments that should be pursued in order to accomplish the backbone supporting research and technology needed to support manned space operations in the coming decades.

Section 5
GENERALIZATIONS ON HUMAN ROLES IN SPACE - TASK 4

The objective of Task 4 was to integrate the analyses and results of the three preceding tasks into an easily accessible procedural format that can provide space project managers and systems engineers with a logical basis for deciding, early in the conceptual design process for advanced systems, which space activities can most efficiently be conducted by manned, supported, augmented, teleoperated, supervised, or independent operations.

We have learned from the U.S. and Soviet* space programs to date that (1) systems can have indefinite operational lifetimes in space if they are designed to permit the contingency of in-flight repair and maintenance; (2) structures too large to be launched intact can be constructed and assembled on orbit using man's unique capabilities; and (3) the flexibility and creative insights provided by the crew in situ significantly enhance the probability of successfully achieving mission objectives.

The ability of the crew to manually assemble delicate instruments and components and to remove protective devices such as covers, lens caps, etc., means that less rugged instruments can be used as compared to those formerly required to survive the high launch-acceleration loads of unmanned launch vehicles. As a result, complex mechanisms secondary to the main purpose of the instrument will no longer need to be installed to remove peripheral protective devices or to activate and calibrate instruments remotely. With the crew members available to load film, for example, complex film transport systems are not needed, and malfunctions such as film jams can be easily corrected manually. The time required to calibrate and align instruments

*The Soviets have been reported to rely heavily on manned involvement in order to repair equipment and subsystems with serious shortcomings in reliable and trouble-free service life.

directly can be as little as 1/40th of that required to do the same job by telemetry from a remote location. In general, physical articulation and movement constraints in teleoperated systems result in performance times that are up to ten times longer then if the same tasks could be performed directly by human operators (Reference 20).

With the availability of extended-duration manned missions, specific experiments and operations no longer will need to be rigidly planned in advance, but can change as requirements dictate. One of the greatest contributions of crews in scientific space missions can be in reducing the quantity of data to be transmitted to Earth. One second of data gathered on SEA SAT, for example, required one hour of ground-based computer time for processing before it could be used or examined, or a value assessment made. Scientist-astronauts in situ could determine in real-time whether cloud cover or other factors are within acceptable ranges before recording and transmitting data.

The astronaut can abstract data from various sources and can combine multiple sensory inputs (e.g., visual, auditory, tactile) to interpret, understand, and take appropriate action, when required (see Figure 5-1). In some cases the human perceptual abilities permit signals below noise levels to be detected. Man can react selectively to a large number of possible variables and can respond to dynamically changing situations. He can operate in the absence of complete information. He can perform a broad spectrum of manual movement patterns, from gross positioning actions to highly refined adjustments. In this sense, he is a variable-gain servo system.

Thus, with the advent of manned platforms in space, there are alternatives to the expensive deployment of remotely manned systems, with their operational complexity and high cost of system failure. Long-term repetitive functions, routine computations or operations, and large-scale data-processing functions can be expected to be performed by computers capable of being checked and serviced by crews in orbit, just as they are now serviced in ground installations. In addition, the normal functions of the terrestrial shop, laboratory, and production staff will find corollary activities in the work done by the crews manning the space platforms of the coming generation.

Men
Surpass Present Day Machines in the Ability to

- Sense or Detect Minimum Amounts of Visual and Acoustic Energy
- Recognize and Interpret Patterns of Light and Sound
- Improvise and Use Flexible Procedures
- Store Large Amounts of Information Over Long Periods and Recall Relevant Facts at Appropriate Times
- Reason Inductively
- Exercise Judgment

Machines
Surpass Man in the Ability to

- Respond Rapidly to Control Signals
- Apply Great Force Smoothly and Precisely
- Perform Routine Receptive Tasks Reliably
- Store Information Briefly and Erase Completely
- Process Information Deductively, Including Ability for Computation
- Handle Highly Complex Operations - Many Tasks at Once

Figure 5-1. Machines Are Extensions of Man's Capabilities

When assessing the relative value of the various categories of man-machine interaction in accomplishing the objectives of future space missions, many different criteria can be suggested as candidates for inclusion in the decision process.

The criteria of performance, cost, and mission success probability (program confidence) are the principal factors that program or project managers and system engineers use in selecting the most cost-effective

approach to meeting mission objectives. The decision maker must base his judgment on knowledge that a particular implementation option can or cannot meet the performance requirements in terms of such factors as force, sensory discrimination, speed, and accuracy. If it can meet the performance requirements, can it do so within the system environmental constraints of temperature, pressure, radiation, atmospheric constituents, mass limitations, acceleration disturbance limits, etc.? In many cases, more than one implementation option can meet the performance requirements, and it is then necessary to examine the relative costs and success probability associated with each approach. While the final selection in the tradeoff between an acceptable probability of success and the resultant cost must rest with the decision maker, the intent of this study was to provide a frame of reference in which the interrelationships of these pertinent parameters can be made visible, and from which rational or informed decisions can be derived.

With regard to performance, 37 generic classes of activities were defined (see Section 3) that, when combined in the required operational sequences, could be used to describe a broad spectrum of potential space programs. For each of these activities and for each category of man-machine interaction (manual, supported, augmented, teleoperated, supervised, and independent operations), the limiting factors in terms of sensing, information processing and motor actions have been defined and the requirements for human involvement were described. As a general statement, response time was found to be the most generally applicable discriminator between the manually controlled modes and the supervised and independent modes of operation. If responses in time periods of seconds or less are required, then the activity is generally best performed in the supervised or independent modes. In the "Activate/Initiate System Operation" or "Information Processing" activity classifications, for example, applications where speed of response would dictate that the activities be performed in the supervised or independent modes might include launch abort procedures and orbital trajectory corrections. If allowable response times become minutes or hours, then all modes might be applicable and the criteria of cost effectiveness or success probability would provide the more appropriate bases for selection of a particular mode of implementation.

With regard to cost, costing models were derived (see Section 3.4) that provided comparative data on the relative costs for each man-machine mode in

performing each activity, from one to many hundreds of times. These comparative costing data were further refined to take into account the commonality that can exist among the equipment items or resources needed to support multiple activities (see Section 3.5).

In developing an estimate of success probability, the study team initially considered two issues. One was the issue of human reliability and how the human can best be used to increase mission success probability; the second was the impact of the state of technological readiness on mission success.

In reference to the issue of human reliability, considerable work has been done in the last twenty years in attempting to develop quantitative indices of human reliability. Swain, (1977)[1] and Swain and Guttman, (1980)[2] have developed techniques for calculating the reliability of complex man-machine systems such as nuclear power reactors by mathematically integrating human and machine error information. Hammer, 1972[3], provided human reliability ratings for over 50 specific manual tasks such as installing gaskets, installing lockwires, removing Marmon clamps, loosening nuts, etc. Recently, the U.S. Navy's Sea System Command has prepared a "Human Reliability Prediction System Users Manual"[4] for use in estimating the impact of human reliability in electronic maintenance and servicing tasks directed toward improving mission equipment availability.

Although precise analytic techniques exist when predicting the reliability of complex mechanical or electrical systems with components of known

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(1) Swain, A. D. (1977). Error and Reliability in Human Engineering. In B. Wolman (Ed.) "International Encyclopedia of Psychiatry, Psychology, Psychoanalysis, and Neurology (Vol. 4, pp. 371-373). New York: Von Nostrand Reinhold.

(2) Swain, A. D., and Guttman, H. E. (1980). Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Application (NUREG/CR-1278). Washington, D.C., U.S. Government Printing Office.

(3) Hammer, Willie, Handbook of System and Product Safety, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1972.

(4) U.S. Department of the Navy, Human Reliability Prediction System User's Manual, Sea Systems Command, Washington, D.C., December 1977.

reliabilities, and some success as noted in the references has been achieved in predicting human reliability factors in certain well structured tasks, considerable caution must be exercised in attempting to treat the analysis and integration of human and machine error in a manner analogous to the techniques used in dealing with physical systems. The basic problem is that human errors are fundamentally different from machine errors. When a physical component fails, the system is usually designed so that the failure is isolated and doesn't affect other components. When humans make a mistake, resulting frustrations may increase the likelihood of subsequent errors. Machine failures generally require human intervention to repair or replace the failed component. On the other hand, humans can monitor their own performance and can often correct their own errors before they affect system performance. In physical systems, redundant components are assumed or designed to be independent and by being placed in parallel networks, can increase system reliability. Redundancy in crew size or presence, however, does not necessarily increase reliability and in fact the social interactions among crew members can lead to common conclusions that may in fact be wrong. On the other hand, the human's perception of the likelihood of the failure of specific components can lead to a greater sensitivity and awareness for impending failure and the potential for anticipating corrective actions. While mathematical modeling of human performance may be possible in well structured tasks, the precise mathematical modeling of human performance for systems in the very early conceptual design phase is an elusive goal.

On the basis of past experience (see Figure 5-2), the basic rule when designing new systems should be to consider the human element not in terms of being a component in series with other system elements and having a specific numeric value of reliability, but rather as an element functioning in parallel with the machine components. The human element can enhance system operations by reducing the risk of system failure through the utilization of human performance capabilities to provide parallel or redundant resources in the form of maintenance/servicing, repair/replacement, and reprogramming of the machine elements.

Based upon today's state of knowledge of human capabilities and limitations it was concluded that human reliability remains a difficult

Machine Characteristics

- Component failures generally independent
- Requires repair or replacement by external agent
- Parallel (or redundant) components assumed to be independent
- Mathematical models can describe machine reliability

Human Characteristics

- Tend to compound errors
- Capability for self-correction of errors
- Social interactions lead to common and perhaps erroneous perceptions
- Variable gain settings in error sensitivity

Conclusions

- Difficult to establish meaningful reliability goals by mathematically combining human error data with machine reliability data
- Enhance probability of success by placing human elements and machine elements in parallel
- Machines monitor humans and humans manage machines

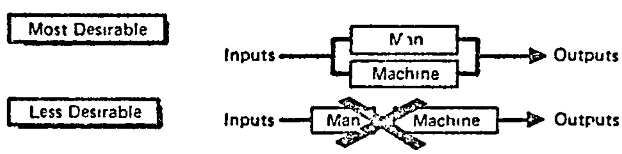

Figure 5-2 Reduction of Risk – The Issue of System Reliability

concept to quantify, especially when dealing with the very early preliminary design phase of advanced systems. Accordingly it was believed that further exploration of human reliability as a numeric indication of the success probability of various modes of man-machine interaction would not be warranted and in fact would be beyond the scope of the present study. Obviously the system designer will find it beneficial to enhance mission success probability whenever possible by providing redundancy in all critical systems and by including the capability for on-orbit servicing and repair. If this approach to advanced system design is followed as a basic design philosophy, it was reasoned that a more immediately useful metric for assessing the success probability of alternative man-machine modes could be based upon the state of technological readiness of the alternative implementation concepts. This then was the approach that the study team followed.

As described in Section 4 of this report, seven levels of technology readiness can be established as follows:

Level 1 Basic Principles Observed and Reported

Level 2 Conceptual Design Formulated
Level 3 Conceptual Design Tested Analytically or Experimentally
Level 4 Critical Function/Characteristic Demonstration
Level 5 Component/Breadboard Tested in Relevant Environment
Level 6 Prototype/Engineering Model Tested in Relevant Environment
Level 7 Engineering Model Tested in Space
Level 8 Full Operational Capability and (FOC) Baselined Into Production Design

Technology designated as off-the-shelf or otherwise reflecting current operational capabilities would be considered as FOC.

Figure 5-3 summarizes the expected relationships between technological readiness levels and time. Simple Systems may be defined as requiring

- Implementation of a singular action.
- Operations generally independent of other functions.
- Unique applications although basic principles well understood.

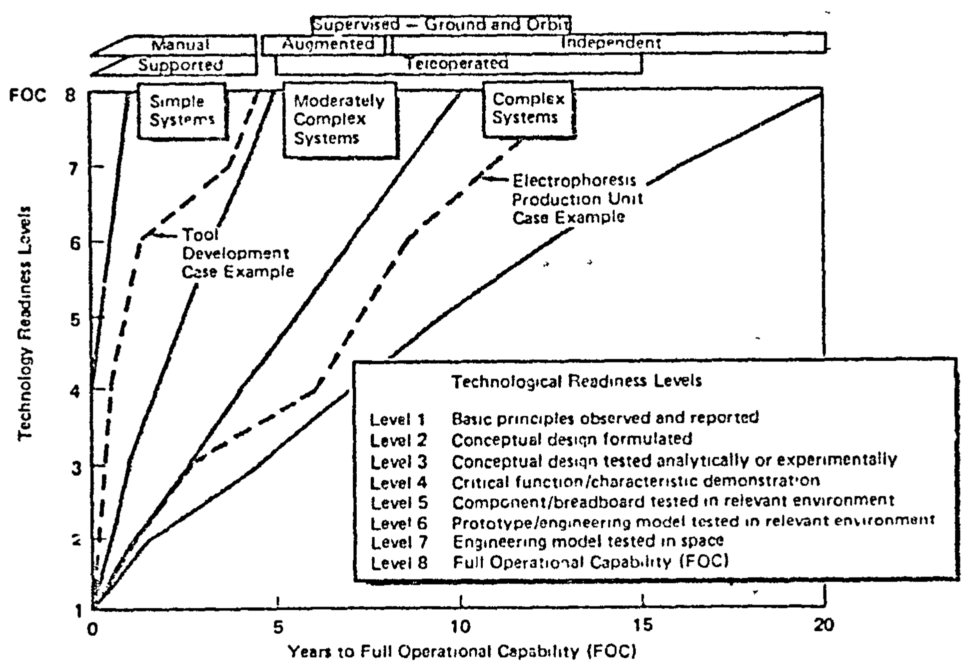

Figure 5-3 Time Required to Reach Various Technology Readiness Levels

An example might be a ratchet wrench which is required to remove and install mechanical fasteners. Most manual and supported modes of man-machine interaction would fall into this category.

Moderately Complex Systems may be defined as requiring

- Multiple interacting functions or actions.
- Complex control logic or networks.
- Basic implementation techniques similar to previously developed systems.

An example might be a computer work station which provides data computation, correlation, and plotting capabilities. Most augmented, teleoperated, and some supervised modes of man-machine interaction would fall into this category.

Complex Systems may be defined as requiring

- Multiple interacting functions or actions.
- Complex control logic or networks.
- Reduction to practice of design concepts. (Comparable system has not been developed.)

An example might be a remotely controlled satellite servicing system capable of self-actuating or self-healing operations in response to external stimuli. Most remotely supervised and independent man-machine interactions would fall into this category.

Based upon the criteria of performance, cost, and technological readiness as developed in Tasks 1, 2, 3, and 4 of the study, the study team has attempted to formulate a decision guide that can be used to logically allocate space activities to alternative man-machine implementation modes. In developing this decision guide, we recognized that such decisions are highly dependent upon the time period in which a given system will be implemented. That is to say, the capabilities to support man in space will continue to evolve as will the other technologies including the applications of artificial intelligence and the advanced development of micro- and macro-manipulators. Furthermore, the index numbers (performance times, cost data, technological readiness, etc.) used in the decision process at this point in time can be expected to change as better information becomes available from future studies and from operational experience. Accordingly, the decision model suggested

below should be considered as still in the evolving stage and should be viewed in that context. Even so, it is believed that the procedure as outlined will prove to be useful in the early conceptual design process to help decision makers formulate a strategy for selecting an initial reference design configuration. As the design concept crystallizes, it would be anticipated that the design solutions would be iterated to take advantage of the better data on performance, cost, and success probability that become available as the design matures. In some cases, it may also be expected that the preferred mode of implementation will change in later stages of the preliminary design process as better design data are developed.

With these caveats in mind, and recognizing that the guide might take many forms, a simplified schematic of the decision process is presented in Figure 5-4. In order to accomplish the steps in this decision process, a worksheet format has been prepared as illustrated in Figure 5-5. An example of how this worksheet might be utilized is illustrated in Figure 5-6.

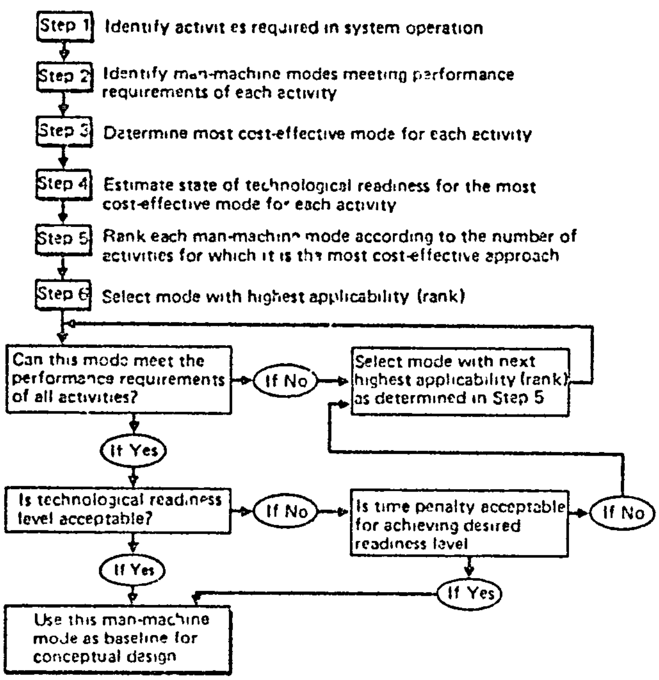

Figure 5-4. Decision Process for Identifying the Man-Machine Mode to Use in the Initial Conceptual Design Effort for An Advanced Space System

No.	Activity Name	Check if Activity Required	No of Times Performed	Man Machine Categories: Manual	Supported	Augmented	Teleoperated	Supervised – Ground –	Supervised – Orbit –	Independent	Technological Readiness (TR)	Cost Ratio for TR of 7 at IOC	Years to TR of 7
		A	B	C	D	E	F	G	H	I	J	K	L
1	Activate/Initiate System Operation												
2	Adjust/Align Elements												
3	Allocate/Assign/Distribute												
4	Apply/Remove Biomedical Sensor												
5	Communicate Information												
6	Compensatory Tracking												
7	Compute Data												
8	Confirm/Verify Procedure/Schedule/ Operations												
9	Connect/Disconnect Electrical Interface												
10	Connect/Disconnect Fluid Interface												
11	Correlate Data												
12	Deactivate/Terminate System Operation												
13	Decode/Encode Data												
14	Define Procedures/Schedules/ Operations												
15	Deploy/Retract Appendage												
16	Detect Change in State or Condition												
17	Display Data												
18	Gather/Replace Tools/Equipment												
19	Handle/Inspect/Examine Living Organisms												
20	Implement Procedures/Schedules												
21	Information Processing												
22	Inspect/Observe												
23	Measure (Scale) Physical Dimensions												
24	Plot Data												
25	Position Module												
26	Precision Manipulation of Objects												
27	Problem Solving/Decision Making/ Data Analysis												
28	Pursuit Tracking												
29	Release/Secure Mechanical Interface												
30	Remove Module												
31	Remove/Replace Covering												
32	Replace/Clean Surface Coatings												
33	Replenish Materials												
34	Store/Record Element												
35	Surgical Manipulations												
36	Transport Loaded												
37	Transport Unloaded												
	Summary Data	M	X	N	O	P	Q	R	S	T	U	V	W
	▭ Man Machine Categories Not Appropriate to Activity Implementation	Total Required		Number of Times Selected							Median Readiness Level	Program Cost Increase	Maximum No of Years

Figure 5-5. Worksheet for Defining the Human Role in Space

	Space Platform Payload No. 2	Check if Activity Required	No of Times Performed	Man Machine Categories: Manual	Supported	Augmented	Teleoperated	Supervised – Ground –	Supervised – Orbit –	Independent	Technological Readiness (TR)	Cost Ratio for TR of 7 at IOC	Years to TR of 7
	Activity Name	A	B	C	D	E	F	G	H	I	J	K	L
1	Activate/Initiate System Operation	√	1	√	√	√	√	NA	√	NA	7	1	4
2	Adjust/Align Elements	√	10	√	√	√	√	NA	√	NA	7	1	4
3	Allocate/Assign/Distribute												
28	Pursuit Tracking												
29	Release/Secure Mechanical Interface	√	300	√	√	√	√	NA	√	NA	6	2 2	5
30	Remove Module	NA	–	–	–	–	–	–	–				
31	Remove/Replace Covering	NA	–	–	–	–	–	–	–	–			
32	Replace/Clean Surface Coatings	NA	–	–	–	–	–						
33	Replenish Materials	NA	–	–	–	–	–	–	–	–			
34	Store/Record Element	NA	–	–	–	–	–	–	–	–			
35	Surgical Manipulations	NA	–	–	–	–							
36	Transport Loaded	NA	–	–	–	–	–						
37	Transport Unloaded	NA	–	–	–	–	–						
		16		4	–	1	1	–	10	–	6	1 4	5
	Summary Data	M		N	O	P	Q	R	S	T	U	V	W
	NA = Not Applicable to this Mission; ▭ Man Machine Categories Not Appropriate to Activity Implementation	Total Required		Number of Times Selected							Median Readiness Level	Program Cost Increase	Maximum No of Years

Figure 5 6 Example of Worksheet Procedure

In using this worksheet, seven modes of man-machine interaction have been selected to represent the steps along the continuum from direct manual operation at one extreme to completely independent self-healing, self-actuating systems at the other. These modes are designated as manual, supported, augmented, teleoperated, supervised-ground, supervised-orbit, and independent and were defined in Section 1 of this report (see Figure 1-1).

Examples of the nomographs that are to be used with the worksheet are illustrated in Figures 5-7 to 5-10. The cost numbers in these nomographs are based upon production and operations costs only (as described in Section 3.4) and do not include design and development costs. It was assumed that NASA will most likely not include nonrecurring costs when developing user charge policies for advanced space systems.

The cost charges for the activities to be conducted in the direct manual modes (manual, supported, augmented, and teleoperated) were based primarily on a cost per unit time factor. On this basis, the delta costs for EVA over IVA

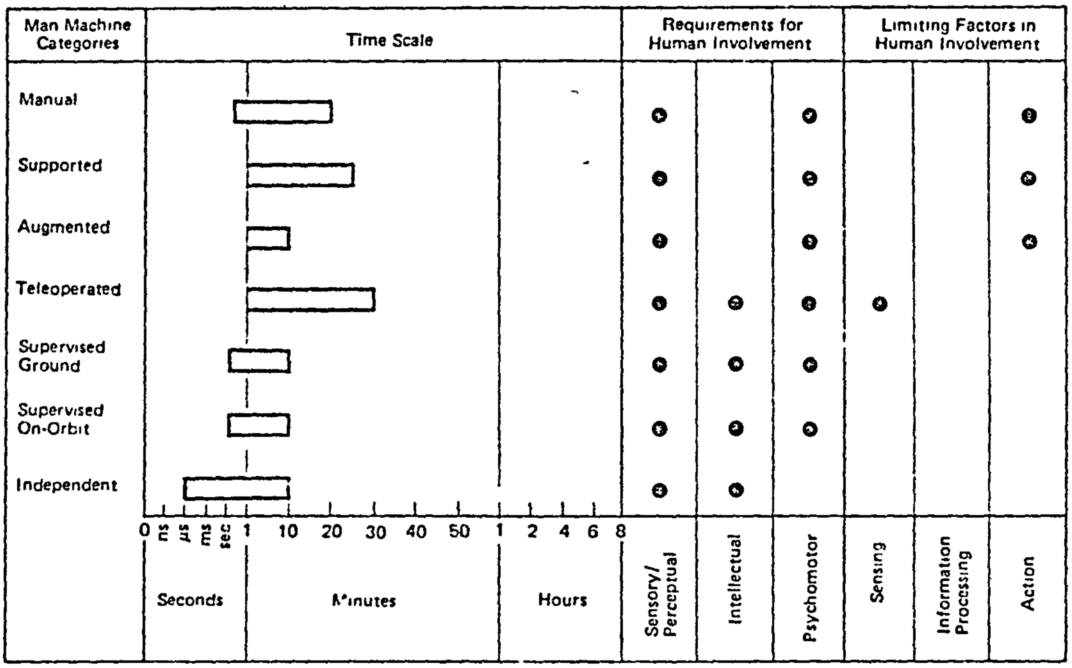

Figure 5-7. Release/Secure Mechanical Interface

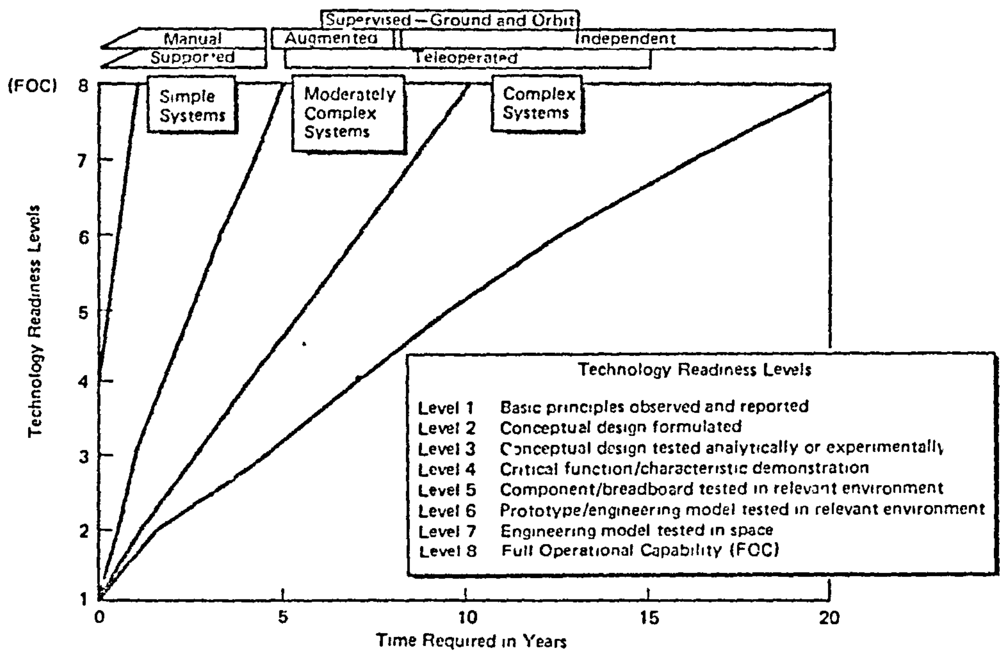

Figure 5 8 Time Required to Advance Level of Technological Readiness

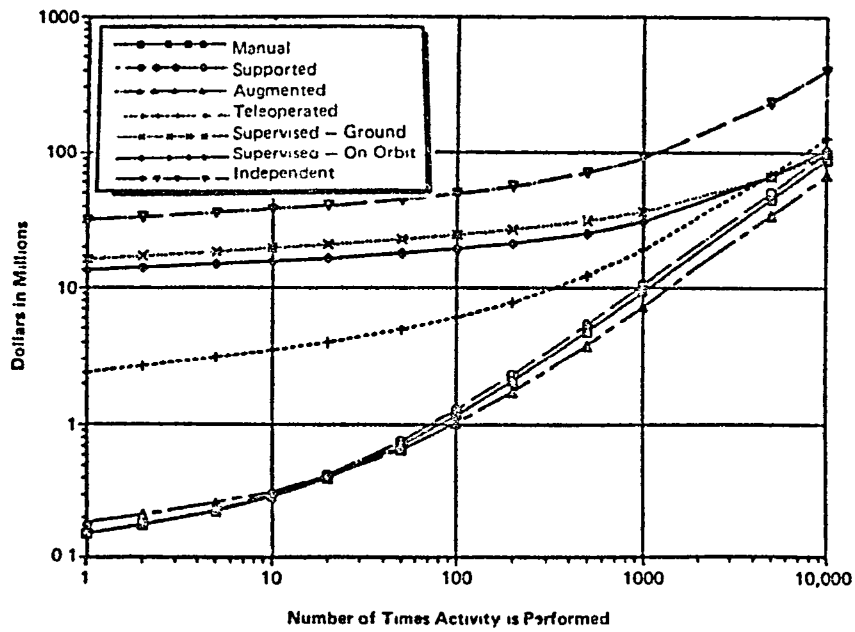

Figure 5-9. Activity Number 29 – Release/Secure Mechanical Interface Cumulative Cost vs. Frequency Including Operations

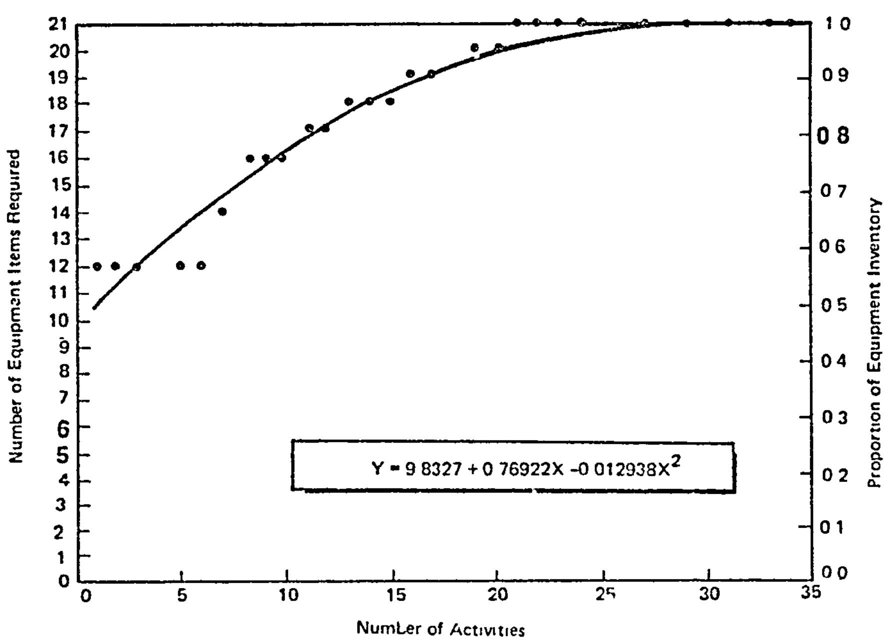

Figure 5-10. Cost Correction for Equipment Commonality

were negligible when compared to the overall cost of manned space operations. Thus, it was not found necessary for the initial approach to selecting the baseline operational modes to determine whether the activity would be done by IVA or EVA. The issue of IVA or EVA can be resolved later in the design process based on more detailed performance and operational requirements, and not by cost per se.

To determine the man-machine category to consider in the initial conceptual design of a space system, six key questions need to be addressed. The suggested procedure for answering these questions is illustrated below.

STEP 1

Which of the 37 unique acivities are involved in meeting the mission objectives?

1. Place a check mark in column A of the worksheet (Figure 5-6) by each of the 37 activities that are required for accomplishing the mission objective.

2. For each activity checked in column A, estimate the number of times that activity will be performed during the mission and enter the numeric estimate in column B.

3. Add the number of checks in column A and enter total in Box M.

STEP 2

Which modes of man-machine interaction can meet the performance requirements of each activity?

1. Consult the timeline charts found in Appendix D that are associated with each activity checked in column A (see sample Figure 5-7). Place a check in each of the man-machine categories, columns C through I, that could be used to satisfy the mission requirements, basing your judgment on:

   - Time requirements for performing activity. If the response time required is seconds or less, the indirect modes (supervised or independent) would be preferred.

- Limiting factors that may restrict human involvement. If limiting factors on human involvement are noted on the timeline charts it may be helpful to consult the Human Capability Data Descriptions in Appendix A.

STEP 3 Which man-machine mode represents the most cost-effective approach to the performance of each activity?

1. For each activity, checked in column A of the worksheet, circle the check mark in column C through I that represents the most cost-effective man-machine implementation mode, as determined from each set of cost vs number-of-times-activities-is-performed curves (see sample Figure 5-9).

STEP 4 What is the state of technological readiness for the most cost-effective man-machine modes identified in Step 3?

1. For the man-machine mode circled in columns C through I, estimate the technolcgical readiness level (see Figure 5-8) and enter this value in column J of the worksheet.

2. Find the median level of all of the technological readiness values entered in column J and enter this median value in box U. This median value defines the overall technological readiness of the aggregate of the proposed implementation concepts for the mission being analyzed.

STEP 5 What is the relative degree of applicability (rank) of each man-machine mode in accomplishing the mission objective?

1. Enter the total number of circled check marks in columns C through I in boxes N through T respectively. These totals indicate the relative degree of applicability of the alternative man-machine modes.

STEP 6 Which mode should be considered as the baseline for initiating the conceptual design of the system?

1. Starting with the most frequently occurring mode (boxes N through T on worksheet) proceed through the iterative process indicated in Figure 5-4.

2. The present technological readiness level of each man-machine mode should be estimated using the criteria listed on Figure 5-8.

3. For the man-machine implementation mode circled in columns C through I for each activity, determine from Figure 5-8 the number of years required to advance from the present technological readiness level to a technological readiness level of 7 and enter in column L of the worksheet.

4. Enter the maximum value in column L in box W. This value represents the estimated development time required to achieve the highest level of technological readiness (minimum risk) for the most cost-effective implementation.

5. Continue the iterative process until an acceptable baseline mode is established. If no single mode is found to be acceptable, it may be necessary to select a combination of modes that represents the minimum number of modes required to achieve the mission objectives within the time constraints imposed.

Other factors to be considered in formulating the initial conceptual design of an advanced space system are the issues of reliability and cost penalties associated with using alternative approaches to increase the technological readiness level and to thereby increase the success probability.

With regard to enhancing operational reliability, it is recommended that wherever possible a manual mode be identified for each activity as backup to the prime mode selected. It is suggested that this backup mode be the least complex level of man-machine interaction (categories C through I) that can meet the performance and technological readiness requirements.

If multiple man-machine modes are determined to be required to accomplish the mission objectives, an overall estimate of the technological readiness of the system can be made by finding the median of the readiness values entered in column J of the worksheet and recording this median value in box U.

To assess the cost impact of increasing the technological readiness level (Success Probability) identified in box U, the following procedure could be utilized.

1. Enter Figure 5-8 with the desired time to IOC. Determine the man-machine modes that can achieve the highest technological readiness levels within the time to IOC.

2. For the activity with the lowest technological readiness rating in column J, examine columns C through I to determine if any of the modes with a higher rating as identified in Figure 5-8 can meet the activity requirements.

3. For those man-machine modes that have higher technology readiness levels, for the activities being considered, use Figure 5-9 to determine the cumulative costs to perform each activity for the number of times identified in column B.

4. Using the cumulative dollar value for the man-machine mode having the lowest cost value as the denominator, compute the relative cost ratios for the applicable modes.

5. Determine the commonality correction factor for the specific activity from Figure 5-10 based upon the total number of activities required in the operational sequence (box M on worksheet). (Refer to Table 3.5-1 for the derivation of this correction factor.)

6. Multiply the cost ratios determined in Step 4 above by the correction factor determined in Step 5. This value gives an approximation of the cost increase ratio required to achieve a higher level of technological readiness for accomplishing the specific activity being considered. Enter this value in column K.

7. Repeat Steps 2 and 6 for each activity where the technological readiness factor is less than 7.

8. For all activities where the technological readiness is 7, enter the value 1 in column K.

9. Find the average of the values in column K and enter in box V. The value in box V is an estimate of the relative increase in program cost required to accomplish the mission objective with the minimal risk (highest level of technological readiness).

The procedural methodology outlined above has attempted to provide a technique for logically determining early in the conceptual design process for

a new space system which of the various modes of man-machine interaction can be used to most effectively perform the activities required.

Our analyses to date have confirmed once again the conventional wisdom that the human role in future space systems will draw heavily upon the intellectual capabilities and the sensory/perceptual capabilities of the human observer. Of all of man's sense modalities, vision is the most important for future space applications. Man's capabilities for recognizing information in various forms and comprehending or understanding (cognition), his capabilities for creative imagination (divergent production), his ability to rigorously structure problems and develop solutions (convergent production), and his ability to make decisions (evaluation) will continue to be essential ingredients in future systems. Many examples from experiences on previous space missions illustrate these capabilities.

Performance, Cost, and Success Probability (technological readiness) remain the principal criteria in determining where along the continuum, from direct manual intervention to independent operations, the mission requirements of future space programs can best be met. By defining a generic set of activities from which systems meeting future mission requirements can be synthesized, and by assigning performance, cost, and technological readiness metrics to each of these generic activities, a mechanism becomes available for developing a logical rationale for optimizing the man-machine interface.

By use of the methodology developed in this study, it will become possible to establish early in the design process the most cost effective design approach for future space programs, through the optimal application of unique human skills and capabilities.

Section 6
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APPENDIX A

HUMAN CAPABILITY DATA

HUMAN CAPABILITY DATA

CAPABILITY CATEGORY - Sensory/Perceptual Capabilities

HUMAN CAPABILITY - Visual Acuity

Definition: Visual acuity is the ability of the eye to see fine details: the resolving power of the retina with respect to details of the image.

Various aspects (types) of visual acuity have been described; these include:

- Minimum perceptible acuity - The ability to see small objects against a plain background.
- Minimum separable acuity - the ability to see objects as separate when they are close together
- Minimum distinguishable acuity - the ability to distinguish irregularities and discontinuities in the contours of an object.

Characteristics: Visual acuity is commonly expressed in terms of the minutes of visual angle subtended by the detail being discriminated.

- The average normal eye can distinguish features that subtend 1.0 minutes of arc, which is equivalent to 20/20 vision on the Snellen chart
- The threshold for minimum perceptual acuity is 0.008 minutes of arc; for minimum separable acuity, 0.4 minutes of arc; and for minimum distinguishable acuity, 0.8 minutes of arc.

Limiting Factors: The effectiveness of visual acuity is affected by the following limiting factors.

- Intensity of illumination
- Amount of contrast between the target and the background
- Duration of the presentation
- Speed of motion of target
- Location in the visual field
- Wavelength of the illumination

Comments: The characteristics and limitations of visual acuity will be more important than any other aspect of visual capabilities in determining man's role in space operations. Acuity plays a significant role in such activities as target detection and selection, accurate alignment, and pattern recognition.

HUMAN CAPABILITY DATA

CAPABILITY CATEGORY - Sensory/Perceptual Capabilities

HUMAN CAPABILITY - Brightness Detection and Discrimination

Definition: Brightness detection is the ability of the eye to identify light at very low intensities; brightness discrimination is the ability to detect a change in the brightness of a light source or the difference in brightness of two or more light sources.

Characteristics: Brightness is commonly measured in terms of millilamberts (mL) which is a measure of luminance.

- The rods or cones in the light-adapted eye can detect luminances as low as 0.004 mL
- Rods in the dark adapted eye can detect luminances as low as 0.00001 mL
- Discrimination can be expressed in terms of the just noticeable difference (jnd) by the formula: jnd (in %) WB/BX100, where WB = the change in brightness, and B = the initial brightness. Generally, a difference of approximately 10% is required to identify a brightness change.

Limiting Factors: The following factors can affect the threshold of brightness detection and discrimination. Although detection and discrimination are both affected by most of the factors, they are not necessarily affected equally by all factors. Limiting factors are listed below in association with the capability that they more strongly affect.

- Detection
  - Wavelength of stimulus
  - Previous light exposure of observer
  - Duration of prior exposure
- Discrimination
  - Shape and size of stimulus
  - Region of retina stimulated
  - Level of illumination on test

Comments: Brightness detection and discrimination are involved in astronomical observation and in some aspects of pattern recognition. The dark-adapted eye is very sensitive in comparison with mechanical light detectors.

HUMAN CAPABILITY DATA

CAPABILITY CATEGORY - Sensory/Perceptual Capabilities

HUMAN CAPABILITY - Color Discrimination

Definition: Color discrimination includes three different perceptions which may be defined separately.

- Hue discrimination - The ability to detect the smallest difference in wave length of two test fields.
- Brightness discrimination - The ability to detect a change in the brightness of a light source or the difference in brightness of two or more light sources (previously defined).
- Saturation discrimination - The ability to detect small differences in the percentage of white light in two fields of identical hues.

Characteristics: The characteristics of brightness discrimination are described under "Brightness Detection and Discrimination". Saturation discrimination is usually considered too difficult to measure for the determination of accurate thresholds.

Hue discrimination will vary with the wavelength. The smallest difference in wavelength that can be detected as a difference in hue when two fields are presented are:

Color	Smallest Difference in Wavelength
Blue	2.5 millimicrons
Green	1.0 millimicrons
Yellow	3.3 millimicrons
Orange	1.5 millimicrons
Red	20.0 millimicrons

Limiting Factors: The following factors can affect the thresholds of color discrimination. Although most factors will have an effect on each of the perceptions (hue, brightness, and saturation) the ones presented are particularly related to hue discrimination.

- Color of light source
- Color of light reflected from nearby surfaces
- Level of illumination
- Surface reflectivity characteristics

Comments: The capability of color discrimination is involved in many operational and maintenance tasks, since switches, wires, and ducts tend to be color coded. Ordinarily, however, the situations will present no challenge to capability limits.

HUMAN CAPABILITY DATA

CAPABILITY CATEGORY - Sensory/Perceptual Capabilities

HUMAN CAPABILITY - Depth Perception and Discrimination

Definition: Depth perception and discrimination may be defined in one of the following ways.

- The estimate of the distance of an object from the observer
- The estimate of the relative distance of two or more objects from the observer
- The difference in parallax corresponding to the minimum distance two objects can be displaced along the line of sight and still be recognized as being at different distances.

Characteristics: Judgment of absolute distance is very inaccurate, judgment of relative distance is, however, very accurate. Angular differences as small as 2 seconds of parallax can be detected. The value of unaided binocular vision in depth perception is greatest for distances less than 20 feet. Beyond this distance monocular cues of textural gradient, perspective, light and shadow, interposition of objects, atmospheric attenuation, etc. are of primary importance in judging depth or distance. With optical aids such as binocular range finders, stereopsis can be used to judge relative distances at much greater ranges.

Limiting Factors: The following factors can affect the accuracy of depth perception and discrimination.

- Distance of objects from eye
- Absence of objects of known size for comparison
- Atmospheric conditions
- Illumination intensity
- Stimulus size
- Monocular versus binocular cues

Comments: The capability of depth perception has played, and continues to play, an important role in crew involvement in space operations. No difficulties have been experienced by crewmen in the use of depth perception. It may be concluded that typical space operations do not normally challenge the limits of this capability. Important examples of tasks performed by crewmen in space which rely heavily on depth perception include: Apollo docking with lunar lander and Apollo docking with Skylab, operation of the Shuttle remote manipulator system, and the use of the manned maneuvering unit in translating to a remote target, e.g., solar max satellite.

HUMAN CAPABILITY DATA

CAPABILITY CATEGORY - Sensory/Perceptual Capabilities

HUMAN CAPABILITY - Peripheral Visual Detection and Discrimination

Definition: Peripheral visual detection and discrimination may be defined as the ability to perform specified visual tasks with the visual stimulus located in various parts of the visual field other than in the central area, i.e., with the image in various locations on the retina.

Characteristics: A large number of parameters must be considered in identifying the capabilities and limitations of peripheral visual detection and discrimination. The following table identifies many of the involved factors and illustrates limits that have resulted from tasks in the military.

Limiting Factors: The following factors can alter the values of both the horizontal and vertical angular limits of peripheral visual detection and discrimination identified in the previous table.

- Brightness of visual object
- Contrast of the object with its background
- Color of the object and color contrast
- Duration of exposure

Comments: Peripheral visual detection and discrimination are basic in normal visual operations and are, additionally, directly involved in a large number of space tasks such as target location, rendezvous and docking, and tracking. Man's capabilities in this category are limited, however, particularly in situations involving the dark-adapted eye. The involvement of man in a space activity based on his peripheral vision capabilities would seldom be at a level below independent or supervised.

		HORIZONTAL LIMITS		VERTICAL LIMITS	
MOVEMENT PERMITTED	TYPE OF FIELD AND FACTORS LIMITING FIELD	Temporal Ambinocular Field (each side)	Naval Binocular Field (each side)	Field Angle Up	Field Angle Down
a Moderate movements of head and eyes, assumed as	Range of fixation	60°		45°	
Eyes 18° right or left, 15° up or down	Eye deviation (assumed)	15°	15°	15°	15°
	Peripheral field from point of fixation	95°	(45°)	46°	67°
Head 45° right or left	Not peripheral field from central fixation	110°	60°•	61°	82°
30° up or down	Head rotation (assumed)	45°	45°	30°•	30°•
	Total peripheral field (from central line)				
b Head fixed, Eyes fixed (central position with respect to head)	Field of peripheral vision (central fixation)	95°	60°	46°	67°
c Head fixed	Limits of eye deviation (= range of fixation)	74°	55°	48°	66°
Eyes maximum deviation	Peripheral field (from point of fixation)	91°	Approx (5°	18°	16°
	Total peripheral field (from central head line)	165°	60°•	66°	82°
d Head maximum movement	Limits of head motion (= range of fixation)	72°	72°	80°•	90°•
Eyes fixed (central with respect to head)	Peripheral field (from point of fixation)	95°	60°	46°	67°
	Total peripheral field (from central body line)	167°	132°	126°	157°•
e Maximum movements of head and eyes	Limits of head motion	72°	72°	80°	90°
	Maximum eye deviation	74°	55°	48°	66°
	Range of fixation (from central body line)	146°	127°	128°	156°
	Peripheral field (from point of fixation)	91°	Approx (5°)	18°	16°
	Total peripheral field (from central body line)	237°	132°	146°	172°•

• Adapted from Wulfeck, J. W., et al, Vision in Military Aviation, WADC Technical Report 58–399, 1958

HUMAN CAPABILITY DATA

CAPABILITY CATEGORY - Sensory/Perceptual Capabilities

HUMAN CAPABILITY - Visual Accommodation

Definition: Visual accommodation is the ability to bring to focus on the retina objects located a short distance from the eye.

Characteristics: Visual accommodation is limited to objects located no closer than approximately six inches to the eye (in adults).

Limiting Factors: Factors that can affect the ability of an individual to visually accommodate with reference to objects located at various distances from the eye include the age of the individual and the characteristics of the visual median.

Comments: Although visual accommodation plays an important role in many of the tasks associated with space operations, e.g., detailed workbench repair, visual inspection and examination of biological specimens, it is not expected that space activities will impose any unique challenges to this capability. The same visual aids that would be used in terrestrial tasks would be similarly applied in space.

HUMAN CAPABILITY DATA

CAPABILITY CATEGORY - Sensory/Perceptual Capabilities

HUMAN CAPABILITY - Detection and Discrimination of Tone

Definition:

- Tone Detection - The capability of the ear to detect sounds of small intensity. The threshold of tone detection is the smallest intensity (lowest amount of energy) at a given frequency that can be detected (intensity is measured in decibels [db] where db = log dynes/cm^2).
- Tone Discrimination - The capability of detecting just noticeable difference (jnd) in the change in the frequency of a stimulus. The threshold of tone discrimination is the minimum amount of change in frequency that can be detected with a probability of 0.5.

Characteristics:

- The threshold for tone detection will vary with the frequency of the tone in approximate accordance with the following table.

Frequency (cps)	db
10	30
100	-30
500	-60
1000	-65
2000	-70
5000	-60
10000	-45

- Regarding tone discrimination, there is generally no ability to perceive a change in frequency in sounds whose intensity is below -20 db.
- For sounds above 20 db, a frequency difference of 3 cycles per second can normally be discriminated for tones below 1,000 cycles per second.
- For tones above 1000 cps, the just noticeable difference (jnd) is usually about 0.3% of the frequency of the tone.

Limiting Factors:

- Tone Detection - Factors tending to affect the capability to detect low intensity sounds include:
  - sound frequency
  - age of listener
  - previous exposure
  - background tones or noise
- Tone discrimination is affected by the same factors as tone detection and, additionally, is influenced by:
  - the loudness of the tones
  - duration of the tones

Comments: Sounds are frequently used as auditory signals in space mission operations, and sounds of different frequencies are used to impart different types of information. Tone detection and discrimination are, consequently, necessary capabilities among space crewmen; thresholds are, however, never approached and the capability is, therefore, not challenged. Additionally malfunctions are frequently detected initially by the crewman noticing the advent of a new sound or a tone change in an existing sound. This auditory capability is useful, but would not normally be considered in operations planning.

HUMAN CAPABILITY DATA

CAPABILITY CATEGORY - Sensory/Perceptual Capabilities

HUMAN CAPABILITY - Discrimination of Sound Intensity

Definition: Sound intensity discrimination identifies the ability to detect a change in the loudness of a sound. The threshold of discrimination is the just noticeable difference (jnd) of loudness change (energy change) to the loudness (energy) of a sound.

Characteristics: Sound intensity discrimination is strongly dependent upon both the tone and loudness of the initial (test) sound. At frequencies between 500 and 5000 Hz a difference of less than 1 db can be detected for sound intensities between 10 and 60 db.

Limiting Factors: The following factors can affect the jnd of a change in sound intensity:

- Sound frequency
- Sound intensity
- Age of listener
- Background noise
- Previous exposures

Comments: Discrimination of sound intensity is not expected to be a widely used capability among crew personnel. Sound intensity discrimination often works in concert with visual capabilities in docking or other continuous adjustment type tasks but it will probably not be of much importance and will not be challenged by man's activities in space.

HUMAN CAPABILITY DATA

CAPABILITY CATEGORY - Sensory/Perceptual Capabilities

HUMAN CAPABILITY - Sound Localization

Definition: Sound localization is the ability of a subject to perceive the direction from which a sound arrives.

Characteristics: Sounds with frequencies up to 500 Hz can usually be located within approximately 10-12 deg. Sounds with higher frequencies (e.g., 3000 Hz) can be located only within about 20 deg.

Limiting Factors: The accuracy of sound localization can be affected by the following factors:

- Direction of the sound in relation to the median plane of the head
- Frequency of the sound
- Loudness of the sound
- Knowledge of the characteristics of the sound

Comments: Sound localization is a factor in the normal behavior and activities of an individual but should not become important in defining the role of man in space operations. Tasks involving man would not be expected to depend upon, emphasize, or challenge this capability.

HUMAN CAPABILITY DATA

CAPABILITY CATEGORY - Sensory/Perceptual Capabilities

HUMAN CAPABILITY - Detection of Light Touch

Definition: Detection of light touch is the ability to detect and to locate the application of a small amount of pressure to the skin surface. This capability may also be defined in terms of "two-point threshold": the ability to detect two pressure points as separate when the distance between them is small.

Characteristics: The threshold for the detection of light touch varies extensively with the area of the body tested. The two tables included below illustrate this condition.

Thresholds for the Detection of Light Pressure

Body Region	Amt. of Pressure Required for Detection (gms/mm^2)
Finger Tip	3
Back of Finger	5
Front of Forearm	8
Back of Hand	12
Abdomen	26
Back of forearm	33
Sole of foot (Thick Area)	250

Threshold for Two-Point Discrimination

Body Region	Distance Between Points
Finger Tip	2-3 mm
Trunk	60-70 mm
Tongue	1-2 mm
Back of Hand	35-40 mm

Limiting Factors: The factors which can affect the threshold of detection of light touch include the following:

- Body region stimulated
- Rate of stimulus onset
- Duration of stimulus application
- Skin temperature

Comments: Detection of light touch, particularly as it contributes to fine manipulative skills, is one of the principal capabilities that establishes man's role in space. A number of activities which have been identified as candidates for space conduct, such as small animal dissection and surgery and repair and assembly requiring precise and exact manipulations, cannot be performed without man's direct involvement.

HUMAN CAPABILITY DATA

CAPABILITY CATEGORY - Sensory/Perceptual Capabilities

HUMAN CAPABILITY - Tactile Recognition of Shape and Texture

Definition: Tactile recognition is the capability of perceiving and understanding the form and distinctive characteristics of objects by touch sensors only.

Characteristics: Tactile sensitivity may be used to distinguish the shape of various objects if the shapes are not similar to each other. Although no general limitations have been identified, extreme care has been used in the development of control knobs that may be recognized by touch alone and would not be confused with each other. Tactile sensitivity may also be used in identifying textures, as long as the textures are sufficiently distinctive. For example, smooth, fluted, and knurled surfaces can be accurately discriminated but different patterns and depths of knurling and fluting are more difficult to distinguish from each other.

Limiting Factors: Practically, tactile recognition is generally a function of the finger tips. Some factors, which tended to limit tactile sensitivity such as the area of the body stimulated, are not applicable in this instance. Skin temperature, however, will tend to affect tactile recognition to the same degree that it affected sensitivity. Additionally, the gloved hand is generally less capable of recognizing shapes and surfaces than the skin surface directly applied to the object. An exception to this may occur in regard to roughened surfaces wherein the material of the glove would catch on the raised elements of the surface.

Comments: There are few, if any, space-related tasks for which man would be selected or rejected because of his tactile recognition capability or its limitations. This capability is frequently recognized, however, in the coding of controls by shape, size, and texture. Requirements for this type of coding may be found in numerous human factors design handbooks.

HUMAN CAPABILITY DATA

CAPABILITY CATEGORY - Sensory/Perceptual Capabilities

HUMAN CAPABILITY - Discrimination of Force Against Limb

Definition: Discrimination of force against limb is the capability of sensing relative amounts of force and changes in force acting against an extremity.

Characteristics: The capability of judging relative amounts of force or resistance acting against the movement of a limb is usually measured and expressed in terms of "difference limen" which is the average difference in force that can just barely be detected; thus, two forces have to differ (by an amount greater than the limen to be detected as being different.

From the results of experiments, it appears that the hand/arm and foot/leg are quite similar in their capability to judge differences in force; also the capability of the hand/arm to judge differences in linear forces was similar to the capability of judging torque forces. The difference limen is much greater for forces of less than 5-10 pounds than it is for forces greater than ten pounds.

(Difference Limen as a Proportion of Force)

	Linear Force		Torque Force
Force in Pounds	Foot/Leg	Hand/Arm	Hand/Arm
1	--	0.21	0.24
5	0.10	0.10	0.09
10	0.07	0.08	0.07
20	0.05	0.07	0.06
30	0.045	0.06	0.06
40	0.04	0.06	0.05

Limiting Factors: The following factors can affect the accuracy of discriminating force against limb.

- Amount of force
- Position of subject
- Fatigue

Comments: The capability of discriminating force against limb is most frequently utilized in control manipulation. The operator of a control can sense both movement and force through his proprioceptive sense. Force and movement are, therefore, the primary sources of control feedback. This capability is consequently used to advantage in the design of controls rather than in the selection or rejection of humans in specific space operations.

HUMAN CAPABILITY DATA

CAPABILITY CATEGORY - Sensory/Perceptual Capabilities

HUMAN CAPABILITY - Discrimination of Limb Movement and Location

Definition: Discrimination of limb movement and location is the capability to sense the rate and direction of movement of a limb and to identify its final location without visual cues.

Characteristics: With training, blind positioning movements can become reasonably accurate. A blind positioning movement is one in which an individual moves a hand or foot in free space from one designated location to another without benefit of visual cues, such as reaching for a control device when the eyes are otherwise occupied. Accuracy is greatest for positions directly in front of the operator. The following table illustrates the decrease in accuracy in terms of the average distance of hits from the center of targets positioned at various positions with respect to an operator.

	Left				Right		
135°	90°	45°	0°	45°	90°	135°	
2.8"	2.4"	2.6"	1.8"	2.2"	2.4"	3.0"	45° up and outward
2.6"	2.4"	2.2"	1.1"	2.2"	2.2"	2.5"	shoulder level
2.8"	2.2"	2.0"		2.0"	2.0"	2.4"	45° down and outward

Tests related to discrimination of limb movement and location were performed by Skylab astronauts but the results were inconclusive and difficult to interpret.

Limiting Factors: Factors that tend to limit the accuracy of discrimination of limb movement and location include:

- Position of target relative to subject (as shown in the above table)
- Posture and orientation of subject (When an individual is sitting or standing on a tilting platform, as opposed to sitting on a level seat, inaccuracies increase rapidly and non-uniformly.)
- Training

Comments: This capability does not appear to be a pacing factor in the selection of man for specific roles in space.

HUMAN CAPABILITY DATA

CAPABILITY CATEGORY - Sensory/Perceptual Capabilities

HUMAN CAPABILITY - Detection and Discrimination of Angular Acceleration

Definition: The capability of detecting the onset of angular acceleration and changes in the magnitude of angular acceleration is usually defined in terms of the physiological threshold which is the smallest amount of angular acceleration, or a change therein, that can be perceived by an individual.

Characteristics: Under ideal conditions, the limits of perception of angular motion (angular acceleration) are dependent upon two factors: (1) the angular acceleration applied; and (2) the time over which the angular acceleration is applied. In general, for an angular acceleration to be sensed by the horizontal semicircular canals, the product of the acceleration and the time of application of the acceleration must be equal to or greater than approximately 2.5 degrees per second. Thus, if a person were subjected to a horizontal angular acceleration (yaw) of 2.5 degrees per second^2 for a 1-second period, he would barely be able to perceive angular motion. If, however, the angular acceleration were 5.0 degrees per second^2, it would require only 1/2 second of this acceleration to enable the person to perceive angular motion. On the other hand, if he were subjected to a 0.25 degree per second^2 acceleration, it would require at least 10 seconds of this acceleration for him to be able to perceive motion. This concept is referred to as Mulder's law, and in equation form is

$$\alpha T = 2.5^{\circ}/\text{sec.}$$

The absolutely minimum acceleration that can be perceived by the horizontal canals, when a theoretically infinite time of application is allowed, is equal to $0.035^{\circ}/\text{sec.}^2$. It is generally believed that the vertical semicircular canals are somewhat more sensitive than the horizontal, and under those circumstances

$$\alpha T\ 2.5^{\circ}/\text{sec.}$$

for the vertical canals. We must always remember, however, that Mulder's constant (2.5°/sec.) holds true only under certain ideal conditions (i.e., in situations similar to the experimental conditions under which Mulder's data were obtained). In real-life situations the threshold may vary considerably, depending upon the state of arousal or upon the motivations of the individual.

Limiting Factors: Factors that can influence the sensitivity of detecting the onset of and changes in angular acceleration include:

- Which semicircular canals (horizontal, vertical, frontal) are stimulated
- A previously applied angular acceleration
- The presence or absence of non-labyrinthine cues.

Comments: The capability to detect and discriminate the onset and magnitude of angular accelerations is involved in the use of the MMU (Manned Maneuvering Unit) and similar devices. Angular acceleration sensitivity would not be expected to be challenged by any role of man in space operations. A more common concern of man's involvement with angular acceleration is the detrimental effects of excessive angular accelerations.

HUMAN CAPABILITY DATA

CAPABILITY CATEGORY - Sensory/Perceptual Capabilities

HUMAN CAPABILITY - Detection and Discrimination of Linear Acceleration

Definition: The capability of detecting the onset of linear acceleration and changes in the magnitude of linear acceleration is usually defined in terms of the physiological threshold: the smallest amount of linear acceleration, or a change therein, that can be perceived by an individual.

Characteristics: The absolute thresholds of linear acceleration sensitivity (otolith function) are measured in two ways: 1) a change of 1.5 degrees in the direction of linear acceleration acting upon the otolith organs can be perceived under ideal conditions; and 2) a change of 0.01 g (9.8 centimeters per second per second) in the length of the linear acceleration vector acting upon the otolith organs has been reported to be perceptible.

Limiting Factors: Factors which can influence the sensitivity of detecting the onset of and changes in linear acceleration include:

- The original direction of the stimulus.
- The original strength of the stimulus.
- The status of the receptors with respect to adaptation.

Comments: The capability to detect and discriminate the onset and magnitude of linear accelerations is involved in docking procedures and similar operations. Linear acceleration sensitivity would not, in all likelihood, be challenged by any role selected for man in space operations. A more common concern of man's exposure to linear accelerations is the detrimental effects the supra-threshold G_x, G_y, and G_z accelerations associated with launches, landings, and spacecraft tumbling.

HUMAN CAPABILITY DATA

CAPABILITY CATEGORY - Sensory/Perceptual Capabilities

HUMAN CAPABILITY - Detection and Discrimination of Vibration

Definition: The capability to detect vibration and to discriminate among various vibratory frequencies and amplitudes may be defined as the combination of frequency and amplitude at which repeated tactile stimuli cease to be identified as discrete events and are sensed as a continuous (vibratory) sensation.

Characteristics: Although the perception of locally applied vibratory stimuli is considered to be a cutaneous sense, a part of the vestibular apparatus, the sacculus is thought to participate in the perception of whole-body vibration exposures. The threshold for vibrations applied tangentially at the fingertips is approximately 10 Hz at 10^{-2} G and 800 Hz at 0.3 G. Whole-body vibrations become barely perceptible at about 2×10^{-3} G at frequencies between 3-7 Hz. The threshold of perception rises rapidly for frequencies lower than 1 Hz and higher than 10 Hz.

Limiting Factors: Factors which can influence the sensitivity of detection and discrimination of vibration include:

- Amplitude and frequency of the vibratory stimuli (discussed under "Characteristics")
- Direction of vibratory stimuli with respect to the body surface being stimulated

Comments: The capability to detect and discriminate vibration is generally involved in human performance; it is not, however, a capability that would be emphasized in assigning human roles in space. Of more interest to man in space is the effects of vibration on human performance.

HUMAN CAPABILITY DATA

CAPABILITY CATEGORY - Sensory/Perceptual Capabilities

HUMAN CAPABILITY - Detection of Heat and Cold

Definition: Heat and cold are detected by sensors in the skin which respond to an increase or decrease in the skin temperature in that area. The threshold for temperature detection is the smallest rise or fall in temperature that can be detected.

Characteristics: The adequate stimulus for both warmth and cold is heat. Cold is not a positive quantity, and temperature does not have the dimension of energy. The threshold stimulus for cold receptors is a fall in temperature at the rate of 0.004°C per second and, for warmth receptors, a rise of 0.001°C per second, both continuing for three seconds. The thermal sense organs record not the temperature of objects, but the temperature of the skin at the depth at which the receptors are situated. Hence, they are stimulated by internal heat as well as by the heat of the environment. The most important temperature is the temperature of the skin. Objects having a temperature close to the physiologic zero, i.e., the temperature of the skin, elicit neither warmth nor cold sensations. On the other hand, even warm air falling on warm skin, such as with fever, arouses sensations of cold.

Limiting Factors: Factors which tend to influence the sensitivity of heat and cold detection include the following:

- Area of the body stimulated
- Pre-stimulus skin temperature
- Adaptation

Comments: Some space station operations may benefit from man's ability to detect temperature changes as well as temperature quality and quantity; these, however, would customarily be unplanned situations and not the type that would define a role for man in their conduct. More commonly, interest is centered on man's ability to tolerate temperature changes rather than his detection threshold.

HUMAN CAPABILITY DATA

CAPABILITY CATEGORY - Sensory/Perceptual Capabilities

HUMAN CAPABILITY - Detection and Discrimination of Odors

Definition: The ability to detect and discriminate odors is a function of the olfactory membrane which lies in the superior and posterior part of the nose. It is stimulated by substances in the air which are volatile, at least slightly water soluble, and lipid soluble. In order to reach the olfactory membrane most substances must be drawn into the nose with purposeful inhalation which is greater in volume and flow rate than normal resting respiration.

Characteristics: Absolute olfactory thresholds vary considerably, depending upon the method of measurement, but agree in indicating very high sensitivity. For example, artificial musk can be detected at a concentration of only 0.00004 mg. per liter of air and mercaptan at 0.00000004 mg. per liter of air. Although the threshold concentrations of substances that evoke smell are extremely slight, concentrations only 10 to 50 tires above the threshold values evoke maximum intensity of smell. This is in contrast to most other sensory systems of the body, in which ranges of detection are very large, 50,000 to 1 in the case of the eye and even much greater in the case of the ear.

It appears, therefore, that the smell sense is concerned more with detecting the presence or absence of odors rather than with quantitative detection of their intensities. Smell can adapt within a few seconds to a few minutes until it is almost extinguished. After adaptation has taken place, the sensitivity of the olfactory cells returns gradually to normal over a period of many minutes.

Limiting Factors: Factors which tend to limit the sensitivity of odor detection and discrimination include the following:

- Nature of the stimuli
- Method of stimulus presentation
- Condition of the olfactory epithelium
- Adaptation

Comments: The capability to detect and discriminate odors is useful in the detection of contaminants in air, water, or food; and, in some instances, in identifying substances by smell. The use of this capability by man in space would, however, be a chance event; it would not be a part of planned mission operations. In addition odor detection is easily extinguished by adaptation or overload; discrimination of individual stimuli in a mixture is poor; detection is non-directional, and significant training is required for accurate identification.

HUMAN CAPABILITY DATA

CAPABILITY CATEGORY - Intellectual Capabilities

HUMAN CAPABILITY - Cognition

Definition: Cognition may be defined as awareness, immediate discovery or rediscovery, or recognition of information in various forms: comprehension or understanding. Information acted upon by the human element can be in the form of figures, symbols, semantic units, behavioral units, classes, relations, systems and transformations.

Characteristics: The terms cognition and perception overlap to some degree. Both perception and cognition are concerned with input information from sensory sources. Perception, however, is concerned primarily with sensory properties and with the cognition of figural units. The complete cognitive process includes operation with symbolic, semantic, and behavioral concepts as well. Perception is midway along a continuum extending from sensing at one end, to thinking at the other. It is the process of organizing and interpreting sensory inputs based upon past experience. Cognition involves a broader range of mental activity including awareness of semantic meaning and abstract concepts.

Limiting Factors: Factors which tend to change the effectiveness of cognitive activities include:

- State of arousal
- Sensory overload
- Environmental stresses
- Fatigue

Comments: Planning and scheduling activities, monitoring flow patterns, target recognition, understanding speech patterns, etc., are examples of the cognitive operations that will be required in future space systems. In the transmission of speech, for example, peak clipping of the signal causes considerably less intelligibility loss than center clipping. Understanding the relative level of cognitive capabilities of humans in recognizing information in alternative forms permits the system designer to select the most efficient design approach for meeting mission objectives.

HUMAN CAPABILITY DATA

CAPABILITY CATEGORY - Intellectual Capabilities

HUMAN CAPABILITY - Memory

Definition: Memory is defined as the retention or storage, with some degree of availability of information in the same form in which it was committed to storage and in connection with the same cues with which it was learned. Memory storage, however, is an essential condition or determiner of cognition. Memory is distinguished from cognition per se by the ability to recall information having once been exposed to the information.

Characteristics: Information storage is of two distinct types: long-term and short-term. Short-term memory storage capacity is generally limited to about eight individual items. The human generally organizes stored information in terms of sensory modality (visual, auditory, etc.). The most significant storage problem occurs because of the potential interference between old ("held") information and new items that present themselves during the holding period. This accounts for the frequent "reversal errors" in information processing. As a general principle, human memory is more effectively utilized as a means of orienting and sequencing information than as a depository for isolated data or symbolic items.

Limiting Factors: Factors which tend to change the effectiveness of memory functions include:

- State of arousal of the human system (alertness)
- Environmental stresses
- Organization/disorganization
- Cumulative disruption
- Fatigue
- Training

Comments: Memory will be essential in long duration space missions for procedures, target characteristics, etc.

HUMAN CAPABILITY DATA

CAPABILITY CATEGORY - Intellectual Capabilities

HUMAN CAPABILITY - Divergent and Convergent Production

Definition:

- Divergent Production - is related to creative imagination. In this process, items of information are retrieved from memory storage and used to generate a number of varied responses. Divergent Production can be defined as the generation of new information from given information where the emphasis is on variety and quantity of output from the same source.

- Convergent Production - is the derivation of logical deductions or at least compelling inferences leading to a unique answer or conclusion. In convergent production the problem can be rigorously structured, and is so structured, and an answer is forthcoming without much hesitation.

Characteristics: The conception of divergent-production abilities came about through investigation of certain hypotheses regarding the component abilities most relevant to creative performance. A factor of fluency was expected, and three kinds of fluency were found; a factor of flexibility was expected, and two kinds were found; and an expected factor of originality materialized. Later, in a study of planning abilities, a factor of elaboration was expected and was demonstrated.

But factors of fluency and flexibility have been found in nonverbal tests as well as in verbal tests. Search among nonverbal tests revealed the parallels essentially complete in figural and symbolic areas of information alongside those in the semantic category. The three kinds of fluency are concerned with the products of units, relations, and systems; the two kinds of flexibility are concerned with classes and transformation, into which category originality fits; and elaboration has to do with implications.

Utilization of DP abilities is observed in tasks that involve the production of information, in quantity and in variety, and sometimes with alterations in that information. Experimental work has demonstrated the forms and conditions needed for optimal utilization of these abilities.

Limiting Factors: The limiting factors which are associated with divergent and convergent production are similar to those associated with other intellectual capabilities.

Comments: Divergent production operations are required in problem solving, development of alternative courses of action, and improving in emergencies; convergent production operations are required for troubleshooting tasks.

HUMAN CAPABILITY DATA

CAPABILITY CATEGORY - Intellectual Capabilities

HUMAN CAPABILITY - Evaluation

Definition: Evaluation is defined as a process of comparing a product of information with known information according to logical criteria and making a decision concerning criteria satisfaction.

Characteristics: It has been found that evaluative abilities may be measured by tests that call for either absolute judgment of the yes-no, disjunctive type or relative judgments of the "which-is-best" type. The former probably has the advantage of providing better experimental control of what is measured.

One of the most important issues when considering the use of this capability in system operations is the definition of the kinds of criteria for judgment that are required in the tasks to be accomplished. The more precise criteria of identity, consistency, and similarity work well in some instances; it is not certain whether they can be universally applied among the many different task applications. In experimental studies, tests with looser criteria of various kinds have been variously successful, indicating some breadth of generality with respect to criteria for evaluation. No criteria of an aesthetic or ethical character have been applied. It is possible that aesthetic or ethical judgments involve new dimensions of evaluative behavior.

Limiting Factors: Limiting factors which are associated with evaluation are similar to those associated with other intellectual capabilities.

Comments: Evaluation operations will be essential for assessing the level of normal or abnormal performance of system elements and, through comparative judgments of "greater than." "less than," or "equal to," to direct system operations in the most expeditious manner.

HUMAN CAPABILITY DATA

CAPABILITY CATEGORY - Psychomotor/Motor Capabilities

HUMAN CAPABILITY - Production and Application of Force

Definition: Muscle force is a function of the following.

- Muscle Tension - Muscle tension is maximum when the length of the muscle is greatest and momentarily there is no change in length. Muscle force decreases as the muscle shortens and as its rate of shortening increases.

- Mechanical Advantage - Power is applied at the point of muscle attachment (i.e., the long bones are the lever arms, and the joints are the fulcrums). Thus, for example, when muscle force of extension is applied at the elbow, power is greatest when the elbow is flexed. However, optimum mechanical advantage occurs at the midpoint of full elbow travel.

  Optimum mechanical advantage more than compensates for the shortened muscle, therefore providing maximum strength at the midpoint. Human muscles in maximum contraction can exert considerable force (as much as 1000 lb, 453 kg), but such forces cannot be fully utilized directly because all muscles work at some mechanical disadvantage, thus reducing output but increasing rate of movement.

The production and application of muscle force also includes the following aspects:

- Strength: The maximum force that muscles can exert isometrically in a single voluntary effort.

- Isometric strength (static): The maximum force that muscles can exert when muscle length remains constant during contraction.

- Isotonic strength: The maximum force that muscles can exert when muscle tension is kept constant.

- Concentric force: The force exerted when the muscle is shortened against an external resistance.

- Eccentric force: The force exerted when the muscle lengthens passively against an external force.

- Effort: Physiological strain, both static and dynamic.

- Work: Dynamic effort (i.e., force times displacement).

- Endurance: The ability to continue work or exert force.

Characteristics: Data are available relating maximum muscle strength to a number of factors including body build, body position, limb position, and age. Values of interest may be found in most human factors design handbooks and are too numerous to be repeated in this document. Selected examples are given below:

o Hand grip strength	134 lbs (mean of U.S. Air Force, male personnel)
o Back lift	350 lbs (mean of males)
o Finger pull	8 lbs
o Forearm lift	60 lbs
o Bench	21 lbs
o Pedal force	60 lbs (from a seated position)
o Lever Force (seated)	45 lbs (fore-aft), 18 lbs (lateral)
o Lever Force (standing)	130 lbs (away from body), 120 lbs (toward body)
o Hand Cranking	40 inch-lbs (plane of cranking perpendicular to operator's frontal plane, 35 inch-lbs (plane of cranking parallel to operators frontal plane)
o Lifting Forces	66 lbs (floor level to knuckle height), 62 lbs (knuckle height to shoulder height), 60 lbs (shoulder height to arm reach)
o Lifting and Carrying	95 lbs (36 inches above floor) 75 lbs (48 inches above floor) 50 lbs (60 inches above floor)
o Moving Large Objects	150 lbs (with no structural push-off support) 149-194 lbs (with structural push-off support) (The value is dependent upon the distance of the object from the support and on the height of the force plate.)
o Endurance	Maximum muscle force can be exerted for no longer than approximately 30 seconds, after which it begins to decrease rapidly. At one minute it is about 60% of maximum; at 2 minutes, about 40%; and at 4 minutes, slightly better than 25%. After four minutes endurance declines more slowly so that at 10 minutes it remains at about 18% of maximum.

Limiting Factors: Factors that can affect the maximum amount of force that can be produced by muscular activities include the following.

- **Age and sex** — In general, adult females are only about two-thirds as strong as adult males. In terms of age, individuals have maximum strength between the ages of 30 and 40. Usually there is a rapid development in strength between the ages of 13 and 19, and this development slows somewhat between the ages of 20 and 25. This is followed by a slower increase in strength to the maximum between 25 and 30 years of age. People begin to lose about 10 percent of their strength by age 40, 15 percent by age 50, 20 percent by age 60, and at least 25 percent by age 65.

- **Body build** — As a rule, people with larger body builds have more strength, although less powerfully built individuals may require less oxygen for a given task requiring strength. Slender persons often are best at performing rapidly fatiguing tasks involving strenuous exercise. Physique does not necessarily correlate with the ability to perform moderate exercise. Normal persons usually show a 30 to 50 percent increase in strength after about 12 weeks of training.

  Strength is affected by health, diet, and the use of drugs, and strength often varies with diurnal conditions (e.g., people usually have maximum strength at about midmorning).

- **Thermal environment** — Heat affects strength adversely (e.g., when temperatures exceed 85°F (29°C), especially under conditions of high humidity). In general, however, low temperature has little effect except in terms of body mobility and finger dexterity. When individuals become acclimated to a hot environment, they generally gain back a great deal of their normal strength.

- **Acceleration** — Although accelerations up to 5 g's do not affect strength, endurance is affected. Arm movements are effective up to about 6 g's, and wrist and finger movements are effective up to about 12 g's. Practical considerations include the following:

Forces acting against the direction of acceleration are decreased.

Forces acting with the direction of accelerations are increased.

Forces acting perpendicular to the direction of acceleration are least affected.

- Emotional Condition — Strength may increase under stress (i.e., fear, panic, rage, or even excitement). However, skill and accuracy generally are degraded.

  It has been demonstrated that, with hypnosis, pull with forearm flexion may increase as much as 26 percent. Increases may also occur when the maximum effort is preceded by a pistol shot or when the subject shouts during the effort.

  Generally speaking, psychological rather than physiological factors determine maximum strength in the "real world".

  It has been noted that white-collar workers generally are about 10 to 20 percent weaker than manual or blue-collar workers. The implications is that the latter are used to a rougher and more strength-demanding environment.

Comments: Two of the more important factors in determining the amount of force that an individual is able to exert in a given situation are body position and limb position.

- Body position — When individuals are not restricted in terms of body position and are provided with appropriate supporting and/or anchoring facilities, they generally will assume a position from which they can apply their maximum force capability. However, this does not necessarily mean that this is always the best position for maintaining lesser force applications for extended periods of time.

Since there is usually a reciprocal response during force applications (e.g., lifting, pushing, and pulling), it is important to provide appropriate support and anchoring conditions, such as a flat, level floor or deck; a solid, stable seat and seat backrest; or a footrest.

- Limb position

Both limb position and direction of force application are important variables in determining the amount of force an individual can apply. Handgrip forces generally are greater if the gripping task is close to the individual's body than if it is at arm's length. Arm strength is greater if the individual can push against a backrest or footrest. Maximum leg force occurs when the individual's knee is slightly bent (in a seated position with the leg just "short" of maximum extension and with the ball of the foot at approximately the same level as the individual's buttocks). Maximum arm force occurs when the force can be applied approximately at shoulder level. For the seated individual, pull force is greatest when the object is positioned at nearly maximum arm length; push force is greatest when the object is positioned at about half the full arm extension.

Lifting capabilities depend on the size, shape, and gripping characteristics of the package being lifted and on the distribution of weight within the package. For example, a package that is too large to allow the individual to wrap his or her arms around it, to grip it securely, or to offset poorly distributed weight (the package's c/g is too far from the individual's own c/g) cannot be lifted or carried without the probability that the individual will drop it, will lose his or her balance, and/or will suffer strain and possibly some semipermanent or permanent injury.

Selected strength capabilities for various lifting and force-application situations are provided on the following pages. Since some of the data pertain only to adult males, a good rule of thumb for applying the guidelines to females is that females generally are about one-third weaker than males.

These factors become all-important in the almost frictionless environment of space. Handholds, footholds and body restraints become the key to any task requiring strength application. Strength values determined in a one-g environment must be extrapolated with caution to the weightless environment since similar anchoring and body positioning is often difficult to obtain. A compendium of values is not available for the zero-g situation.

Of course, moving large objects in space is much more simple. No limits have yet been set on the mass of an object which is practical to maneuver and translocate in space. Size, restricting both visibility and positioning, appears to be much more of a constraint than mass.

HUMAN CAPABILITY DATA

CAPABILITY CATEGORY - Psychomotor/Motor Capabilities

HUMAN CAPABILITY - Control of Speed of Motion

Definition: The most easily identifiable and measurable manifestation of control of speed of motion is reaction time or response time. This capability is generally considered at two levels. Simple reaction time is the shortest time between the moment a sensory receptor is stimulated and the time some body element reacts. The measurement of simple reaction time, however, typically involves a defined response, such as pressing a key, which allows a comparison of the reaction time of various sensory channels to be included in the measurement. Complex reaction time is a demonstration of the capability in which information-processing time is included in the measurement. Customarily the subject is asked to recognize one stimulus from among several and to respond by selecting one of several response modes.

Characteristics: Response time may be considered a function of several factors, including:

- The sensory channel through which the stimulus is initiated.
- The signal or stimulus characteristics.
- The complexity of the signal.
- The signal rate.
- Whether anticipatory provisions are present.
- The response mode, e.g., the body member used.

Tests involving key response have demonstrated the reaction times for various input channels (e.g., hearing, 0.15 sec; touch, 0.16 sec; and sight, 2.0 sec).

The following estimates have been made regarding the several components of a complex reaction. Time: Stimulus detection and neural transit time, 0.1 sec; brain recognition time, 0.4 sec; decision-making time, up to 4.0 sec; and motor response time, 6.0 sec.

Other generalizations of interest include the following:

- It generally takes about 20 percent longer to respond with the feet than with the hands.

- The preferred hand is usually about 3 percent faster than the nonpreferred one.

- Everyone has a refractory period of about 2 to 3 seconds, regardless of a stimulus demand rate, which means that a second stimulus arriving within 0.5 seconds will be treated together with the first.

- Simple reaction times usually can be reduced by as much as 40 percent by providing an alerting signal.

Limiting Factors: Factors which tend to limit control of speed of motion and alter response time include the following:

- Signal intensity: The greater the intensity of the signal, the faster will be the reaction time.

- Signal anticipation: When the signal is anticipated, reaction time is typically shorter.

- Practice: Reaction time tends to be reduced with practice.

- Pacing: If operators can set their own pace, they can often react faster to known signals.

- Signal quality: Operators generally can react faster to a high-pitched sound, a brighter light, a larger visual target, a longer-duration signal, and a signal emanating from a particular location.

- Likelihood of signal appearance: The least likely signals will have the longest reaction times.

- Signal format: When signals are arranged sequentially or are meaningfully grouped, reaction time is typically shortened.

- Overload: Although an operator can adjust to excessive signal rates by relying on memory for short bursts, total response failure may occur when rates are too high for too long.

- Number of response choices; e.g., 1 choice, 0.20 seconds; 7 choices, 0.60 seconds.

- Reach distance.

- End point control and precision (in contradistinction to the end point being automatically controlled).

- Added manual force required by response.

- Distraction.

- Physical and psychological stress.
- Workplace constraints.
- System feedback.

Comments: Control of speed of motion, response time, and reaction time are essential elements in crew tasks. In general, this capability has its most significant impact on task design. Some operations, however, which involve extremely brief response times would be inappropriate for man's involvement. These usually must be identified on a function-by-function basis.

HUMAN CAPABILITY DATA

CAPABILITY CATEGORY - Psychomotor/Motor Capabilities

HUMAN CAPABILITY - Control of Voluntary Responses

Definition: Voluntary control of movement is part of the perceptual-motor process involving coordination between one or more sensors, the brain, and the musculoskeletal system. Voluntary movements are generally classified as tension movements or ballistic movements. Tension movements are slow intense movements created by the contraction of antagonistic muscles operating one against the other with unequal tension. Ballistic movements are free and generally more rapid, since the simultaneous operation of antagonistic muscles is at a minimum.

Characteristics: Because of the complexity of voluntary response control, few specific tests and measurements can be devised which accurately define its characteristics. The following generalizations may be used to better understand the capacities and limitations of the capability.

- Sensorimotor control between any of the sensory channe~~ls and the~~ hands is generally more accurate and reliable than that between the sensory channel and the feet.

- Hand and arm movements coordination is better when these movements are close to the body and symmetrical.

- Arm movements that progress forward and/or away from the body are more accurate than arm movements that are directed toward the body. The same is true of leg movements.

- Right-handed individuals are more proficient at making clockwise movements than at making counterclockwise movements; left-handed individuals are just the opposite. However, all people make clockwise movements better with the right hand, and counterclockwise movements better with the left hand.

- Generally, a person can rotate his or her hand and wrist more precisely in one direction than another.

- Multiple arm and/or leg translatory movements are more efficient when they are similar, i.e., moving the left hand to the left or forward while at the same time moving the right hand to the right and forward.

- A person can apply force more accurately to two simultaneously operated controls when the controls are located symmetrically with respect to the body and when the directions of movement are similar.

- When separate and different kinds of controls are operated simultaneously, there is a high probability that the operation of one or another control will suffer in terms of operator input efficiency.

- Combined movements, such as trying to push and precisely rotate a control at the same time, almost invariably introduces inaccuracy in one of the motions.

- Excessive disparity between two manual operations often results in a complete breakdown of the sensorimotor response of one of the activities.

- Continuous feedback is desirable in order for most control movements to remain optimized, that is to maintain an accurate direction, force application, and/or rate of movement.

- On the basis of proprioceptive feedback, individuals judge extent of movement more accurately than movement force applied, and force more accurately than duration of movement.

- Although visual control is more important while an individual is learning a new perceptual-motor task, as performance becomes habitual, proprioceptive feedback may become the more important feedback resource.

- When less than 0.5 second per movement is required, blind movements are as accurate as when using visual positioning.

- When the rate of movement is constant, accuracy diminishes as the interval between movements increases.

- It takes about 0.04 seconds to develop maximum tension.

Limiting Factors: Factors that tend to affect the speed and accuracy of voluntary response control include the following.

- Mental set.

- Practice and training.

- Motivation.

- Physical characteristics of the workplace.

- Environmental factors.

- Fatigue.

Comments: Tasks requiring highly refined and coordinated movements are most often allocated to man because of the technical difficulty and cost of producing machines that are capable of similarly refined movements. This capability is the governing factor or is significantly involved in the assignment of man to numerous roles in space operation.

CAPABILITY CATEGORY - Psychomotor/Motor Capabilities

HUMAN CAPABILITY - Continuous-Adjustment Control (Tracking)

Definition: In continuous adjustment or tracking tasks some input specifies the desired output; this may be constant or variable. The input is typically received directly from the environment. If the input is sensed mechanically, it may be presented to operators in the form of signals on a display. The input signal is commonly referred to as a target, and its movement is called a course. The target can usually be described mathematically and shown graphically. The input, in effect, specifies the desired output of the system. The output is usually brought about by a physical response with a control mechanism. In some systems output is reflected by some indication on a display commonly called the controlled element.

Characteristics: In continuous-adjustment control tasks, control effectiveness depends on, at least, the following factors.

- The ability of the operator to anticipate what is going to happen when he provides input to the system.
- The ability of the operator to predict what will happen when he makes specific system inputs.
- Feedback on a timely basis about what is happening as the operator makes control inputs.
- How much differentiation, integration, and/or algebraic addition the control and display task requires of the operator.
- How well the specific control and display devices provide compatible relationships between the operator's sensory, perceptual and motor and physical characteristics.

Two types of tracking tasks are generally recognized:

- Pursuit tracking - A tracking task in which the operator's control and display system provides separate indications for input and output; i.e., the operator makes inputs into the control and then to a display element to follow a target.
- Compensatory tracking - A tracking task in which input and output signals are presented to the operator in terms of a difference between the system and the operator's control input.

Limiting Factors: Factors which can affect the effectiveness of the control include the following:

- The duration of the delay between inputs.
- The amount of noise in the system.
- The relationship between control and display direction and rate of motion.
- Controller force requirements.
- Relationship of the position, direction, and range of movement of the controller with the operator's musculoskeletal system and operating position.
- The number of controls requiring integrated operation.
- Operator's fatigue.

Comments: Humans have proven themselves most competent and efficient in certain continuous-adjustment tasks, such as rendezvous and docking activities, particularly when sufficient preview of the "track ahead" is available. A blanket statement cannot be made regarding the allocation of continuous-adjustment tasks to man or machine. Each situation should be judged within itself to determine if the factors are present which will permit man to perform effectively.

HUMAN CAPABILITY DATA

CAPABILITY CATEGORY - Psychomotor/Motor

HUMAN CAPABILITY - Arm/Hand/Finger Manipulation

Definition: This human capability describes the ability to accomplish tasks involving fine, detailed, and precise movement of the fingers, hands and arms, such as those used in handling small items and specimens, assembling small parts, and in fine adjustment of controls.

Characteristics: Because of the varied nature of manipulative movements, no quantitative data have been developed concerning their characteristics or limitations. The following generalizations have been made regarding finger dexterity and control operation accuracy. Although certain people develop considerable dexterity with practice, the average person is able to perform certain types of control manipulations more accurately than others.

- Rotational manipulation is more accurate than sliding manipulation or movement of thumb or finger wheels, although the latter is more accurate than the sliding manipulation.
- Rotation in the horizontal plane is generally more accurate than rotation in the vertical plane, although the horizontal accuracy depends on the ability of the operator to rest his or her hand on the adjacent surface.
- A pencil-sized joy stick is manipulated more precisely than one requiring a full fist grip, and the accuracy is increased significantly if the operator can rest his or her arm on a nearby horizontal surface.
- An L-shaped handle is more accurately positioned than a round knob, such as a doorknob.

Limiting Factors: Factors which tend to influence the effectiveness of manipulative movements include:

- Light intensity.
- Temperature.
- Training (familiarity with task).
- Alertness/Fatigue.
- Design of work area.

Comments: Man's manipulative skills are among his major assets with respect to his role in space operations. Numerous tasks, particularly those associated with the operation of research laboratories, require manipulative movements which would be extremely difficult (if not impossible) and costly to automate.

HUMAN CAPABILITY DATA

CAPABILITY CATEGORY - Psychomotor/Motor Capabilities

HUMAN CAPABILITY - Body Positioning

Definition: In this context, body positioning refers to setting up the body as a work platform in a coordinated fashion. The function includes neuro-muscular facilitation, muscular strength, and proprioception.

Characteristics: The only definitive values that have been developed relative to body positioning are those associated with the limits of body movement from various positions. These are termed functional dimension of the body and are available in human factors handbooks. Values are customarily presented in terms of population percentiles, e.g., 5th, 50th, and 95th percentiles.

Limiting Factors: Task-associated body positioning accomplished in the 1-g environment will be altered significantly in the weightless environment. The restraint system, including footholds, handholds, and torso restraints, available for the task will, to a great extent, govern the approach taken for body positioning. Under certain conditions significant limitations may be placed on performance because of this dependency on available restraints.

A second factor associated with extra-vehicular operations is the restrictions placed on body positioning by the EMU. Rigorous human factors design principles must be incorporated into the configuration of any system and its components that is a candidate for EVA maintenance or replacement in order to be responsive to the restrictions on normal body positioning.

Comments: Body positioning and the limitations imposed by the space situation must be considered in any allocation of tasks to man which require whole-body involvement.

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APPENDIX B

- OWEN GARRIOTT INTERVIEW
  APRIL 10, 1984

- OBSERVATIONS DURING THE
  SOLAR MAX REPAIR MISSION

Interview with Owen K. Garriott
April 10, 1984

1. Based on your Skylab and Spacelab experiences, what are the lessons learned or technology gaps that should be considered in defining the human role in future space systems?

A fairly complete summary of my observations on Skylab appeared several years ago in Science (18 Oct 1974, Vol. 186, pp 219-226) (see Reference 33). I have also prepared a summary of Spacelab I events and it appears in the July 13, 1984 issue of Science magazine (see Reference 34). These observations should be of interest to you. Technology has improved from the lessons learned on Skylab and much of it has been built into Spacelab.

The use of a computer in particular in Spacelab was very helpful for scheduling and other types of activities. There was no such computer on Skylab.

The Spacelab was not designed to be repaired by the crew because of its short duration mission. Things did fail, however, and we had to again prove that man was capable of developing workarounds and fixing things when they break.

2. What have been your observations on the Space Adaptation Syndrome? Can the crew maintain their ability to work while experiencing these conditions? Can they mentally override the discomfort?

In my experience, not everyone has been subject to this syndrome. For example, on Skylab only two individuals suffered noticeable effects. In any event, however, when the crew is going through this time we should try to keep their workload to a minimum. Physical activities are not impaired by SAS but mental activities do suffer because of the lethargic state that SAS can induce until adaptation occurs. This state of lethargy can last 2 or 3 days.

3. When performing a manual task, what did you find to be the preferred body orientation? Did you use your hands or feet to ground out torques?

On the general subject of restraints, I strongly recommend the use of foot loops which enable the crewmen to have both hands free for work purposes. While working, you normally have a checklist in one hand and are using your other hand to flip switches or whatever. I recommend the addition of many more loops for Spacelab. The foot loops are nice because you can use them for restraint, but when not in use they lay flat and are not an obstruction on the floor. With reference to body orientations for performing tasks, it doesn't really matter if you're upside down or not just as long as you're in the same orientation as the panel you're working at.

4. It has been reported that the deployment of the camera in the Space Lab Airlock was a difficult operation. Is this a task that might be better done in the automated mode rather than manually?

Manual deployment was not bad, the hard part was latching the 5 or so doglegs to secure the hatch (this requires about 50 lbs of force to accomplish). With regard to making it automated rather than manual, "Absolutely not!!". As an example, during a shift change on Spacelab, I was coming on and the first order of business was to deploy the airlock. The shift going off had installed a locking pin in the deployment mechanism, but didn't pass that information on. When I attempted to crank it I immediately felt something was wrong and had to wake up the crewman who went off. If automated, something could have been damaged.

5. In your experience, how realistic are the proposed timelines for future space station missions; e.g., the CDG concept of each person working 9 hours/day, 5 days/week?

Ground prepared pre-mission timelines are sometimes good and sometimes not. For easy predictable activities like system activations or deactivations, flipping switches, or other things along those lines, the timelines are good. However, timelines for experiments like fluid physics were off by about a factor of three and this was because the experiment required real-time reactions in order to accomplish the experiment. As a result of this the mission specialists had to do what they could during the scheduled mission times and they had to add an extra day just to finish the experiment. Experiments can't always be accurately simulated in advance when dealing with unknown results. Work schedules for the 10 day mission were good based on 12 hours/day and should not be changed. I don't particularly care for 5 days/week and 9 hours/day. I suggest scheduling for 9 hours, but having the shifts run for 12 hours. My rationale is that you have to divide 24 hours evenly either by 2 or 3 which results in 12 or 8 hour shifts respectively.

6. Do you have any observations on any other limiting factors on human involvement that should be considered when planning future missions?

I don't have any particular observations relative to human limiting factors. Intersocial activities are important for missions like Skylab or Space Station. When you work in such close quarters it's important for the individuals to have separate sleep areas so they have a place to go to be by themselves. Another important area is that the crew who works together needs to train together. Everyone in the team needs to know what everyone's work responsbilities are and what the person's feelings and weaknesses are. For example, MDC has an engineer flying on the next shuttle, but very few people in the astronaut office know who he is. However, he has been working with the crew and they know him, hopefully!! Also, schedule 1 hour/day for exercise.

7. **Can you cite any critical events that have occurred in previous missions that in turn will help define the human role in future missions?**

In-flight repair of Skylab not only saved the program from near disaster but also was an essential element in the completion of most of the experimental objectives.

(Ed. note - Owen Garriott's article entitled "Skylab Report: Man's Role in Space Research", Science, 18 Oct 1984, Vol. 186, pp. 219-226, gives an excellent summary of the critical events that required human participation during the Skylab missions.)

Spacelab as well benefited from the human presence. A substantial amount of the experimental operations and data were saved through the innovative maintenance and repair capabilities inherent in the crew. For example, the High Data Rate Recorder (HDRR) tape transport jammed and was cleared by hand. In preparation for flight, no maintenance training for this failure was provided, but the crew was helped by having become familiar with the unit during training for a tape change. On the other hand, one experiment used a small tape recorder to generate visual images to present to one eye in a vestibular test. Although the tape recorder jammed, the crew was instructed not to attempt a repair. Postflight inspection revealed that the problem could have been readily fixed.

The flexibility and innovation represented by having the crew available is a resource which should be capitalized upon. However, preflight crew training should include general familiarization with almost all moving equipment items.

8. One of the most important issues in designing future mission operations is to make proper utilization of human intelligence whether on the ground or on orbit. Do you have any comments in this regard?

Man's presence is important for conducting various types of experiments. The crewman performing the experiment may not be an expert in the field of study for that task, but he is able to interact with the ground-based PI's and still be able to obtain good data from the experiment. An analogy might be the crewman serving as the end-effector for the PI/Remote Manipulator. Both Skylab and Spacelab are good examples of this type of interaction.

9. Are there any specific aids and/or support equipment that in your mind could significantly increase the effective utilization of human intelligence in space?

Controls and displays need vast improvements which can better utilize the human. The dynamic evolution of software can be incorporated to provide better details rather than the present 2 dimensional TV displays. A lot of development is required in this area.

10. It has been suggested that a display system that could pictorially pinpoint the crewman's/experimenter's location with respect to the earth would be very useful in order to know what to do and when to do it prior to the target appearing. Is there a need for such a display?

It is very important for the crewmen/experimenter to know where his relative position is with respect to the earth. For example, the ground track data at Mission Control is not available on orbit. For Spacelab we had an electronic instrument (from a Silicon Valley company) which showed where we were plus we could input information for specific targets plus a few other bells and whistles. J. Young liked it so much that it may fly on all flights from here on out.

11. How adequate have the IVA lighting facilities been to date? How does Spacelab compare to Skylab in this respect?

Lighting was good on both Skylab and Spacelab with no light problems anywhere. Since we know what the interior design is, it can be mocked up on the ground to determine the necessary lighting requirements. Not much else to say about this.

12. Are there any functional limits to human performance in space that you can foresee?
    a. Limits based on human senses and motor limitations?
    b. Limitations restricting humans ability to use their senses or motor capabilities at a given time due to: radiation exposure; debilitating effects of zero-g, i.e. muscle atrophy; etc.

With reference to the first question, I can't think of any scheduled activities that were compromised by human limits.

My feelings on radiation exposure are that people should not and will not be exposed to high levels of radiation. The effects of long-term exposure to zero-g are signified by the loss of muscle tone in the lower body. Therefore, physical training is required in order to keep those muscles in shape. My opinion is that 1 hour per day for physical training is sufficient. Neuromuscular weakness is not evident in space; it is only noticed after return to Earth.

OBSERVATIONS DURING THE SOLAR MAX REPAIR MISSION

During STS FLight 41-C (the Solar Max Repair Mission) two THURIS Study team members, R. J. Dellacamera and S. M. Chucker, were present at the Mission Operations Control Center at JSC, to observe the crew performance and interaction during this mission and to obtain data/information pertinent to the continuing definition of the human role in space.

STS Flight 41-C was launched on Friday, April 6, 1984, and was scheduled to perform two primary missions. The first was to deploy in orbit the NASA/LRC Long Duration Exposure Facility (LDEF) and the second was to capture, repair and redeploy the Solar Maximum Spacecraft (SMM).

The first scheduled EVA was set for Sunday, April 8, where the crewmen were to capture the SMM by means of the Manned Maneuvering Unit (MMU), stop the spacecraft's 1^{o}/sec rotation and permit the RMS to capture the SMM and install it in the Flight Support Stand (FSS) where the maintenance activities would take place. They were then to change out the failed attitude control module which would have concluded the first EVA. However, the retrieval operation did not proceed as planned. Nelson and his MMU approached the spacecraft and matched its rotation rate, but when the T-pad impacted the trunnion, the jaws did not release and he bounced off the satellite. Two other attempts were made; however, those too were unsuccessful. One other attempt was made to stabilize the satellite's motion and that was to grab one of the solar arrays and stop the rotation. Although this attempt was unsuccessful, it was later found to have improved the solar array-to-sun angle thus allowing the batteries to achieve a 100% recharge. The unsuccessful attempts to retrieve the SMM resulted in an increase in the satellite's

rotation rates from 1^{o}/sec in roll only, to 1^{o}/sec in roll and pitch and 0.6^{o}/sec in yaw. The MMU retrieval was discontinued because the available propellant was approaching a red line condition. At this point, the EVA was terminated in order to re-evaluate the repair mission alternatives.

<u>OBSERVATION</u> - These unsuccessful attempts could have been successful if the human operator could have manually triggered the jaws in the T-pad mechanism. Risk of failure could have been reduced by designing for redundant manned operations.

The decision was made to attempt an RMS rotating grapple of the spacecraft, if the rotation rate could be reduced. The Payload Control Center activated the spacecraft's torquer bars in order to stabilize the vehicle. Since this operation requires 24 to 36 hours, the Shuttle initiated a separation burn to conserve fuel rather than having to station keep.

On Tuesday, April 10, the Shuttle approached solar max to attempt the rotating grapple. By this time, the spacecraft had been stabilized to a 0.5^{o}/sec rotation in the roll axis and had a slight coning angle of about 15^{o}. The RMS went into a communications blackout region just as the RMS grapple operation began. When communications were reestablished the crew indicated they had captured the spacecraft.

The baseline mission schedule was modified and the second EVA, scheduled for Wednesday, April 11, was changed to accomplish all of the repair activities at one time. The actual repair operation went very smoothly since the crewmen had performed these tasks several times during the WETF training simulations. The maintenance interfaces manipulated by the crewmen were as follows:

Attitude Control Module -

The mechanical attachment consisted of 2 large Acme bolts each tightened to 100 foot-lbs and requiring 8 revolutions to undo the interface. The electrical interface was accomplished through a self-aligning, blind-mated connection. A special battery-powered torque wrench tool was used to access the Acme bolts.

Coronagraph's Main Electronics Box (MEB) -

A hinge had to be attached to the MEB to allow the box to swing out to provide access to the 11, D-series electrical connectors. These connectors were held down with a total of 22 screws requiring 4 turns each. There was a special powered screwdriver set used to remove both the electrical connectors and mechanical attachments. When the new MEB was installed it again interfaced with the hinge to allow access for installing the electrical connectors. The reattachment of the electrical connectors made use of spring clips rather than the 22 screws.

Van Hoften commented after removing the ACS module that the torque wrench tool worked very well.

<u>OBSERVATION</u> - With proper tools, any task that can be accomplished by a human operator on the ground can be accomplished in orbit.

During this EVA operation, the Nikon 35mm camera experienced a film jam. Nelson removed the thermal covering, removed the power drive and unjammed the frame that was stuck (while in the EMU). He then reversed the process, reassembled the unit, and was thereby able to salvage the 35mm photos.

<u>OBSERVATION</u> - Human ingenuity can be used to handle contingency operations, develop workarounds and increase mission success probability.

Van Hoften reported that about 50% of the solar array cells were delaminated. Meanwhile, the ground was receiving good power indications from the spacecraft.

<u>OBSERVATION</u> - Human Sensory/Perceptual processes can sense and detect changes in state or condition that would be very difficult to instrument for remote monitoring.

A photo recon of the satellite was performed for about 30 minutes. The crewman was in the manipulator foot restraint (MFR) for this operation.

OBSERVATION - The success of this operation was highly dependent upon the effectiveness of the communication interaction between the EVA and IVA crewmen.

The crewmen performing the SMM repairs ended up about an hour ahead of schedule. The timelined mission was to take about 4 hours and 50 minutes, while in actuality they completed the mission in just under 4 hours.

OBSERVATION - Timeline data derived from ground based and neutral buoyancy simulations are accurate enough to be used for mission planning purposes.

After the repairs were completed, the spacecraft was checked out to verify that the modules had been properly installed. To do this, the ground activated the heaters in the two new modules and they received a positive indication that they were functioning. During this time Van Hoften took the opportunity to perform some additional evaluations of the MMU's operation.

OBSERVATION - The capability of the human operator to redefine procedures, operations and/or schedules to take advantage of fortuitous opportunities for data gathering can significantly enhance the value of technology development missions.

The second EVA was then terminated after a successful repair mission. The FSS rotated the spacecraft around to provide access for the RMS. The RMS then grappled the spacecraft and lifted it from the FSS. At this point, the ground commanded the deployment of the TDRS antenna on the SMM and the spacecraft was released.

OBSERVATION - The classes of generic space activities (as developed in the THURIS study) which were observed during this mission included the following:

1. Activate/Initiate System Operation
2. Adjust/Align Elements
3. Communicate Information
4. Confirm/Verify Procedure/Schedule/Operations
5. Connect/Disconnect Electrical Interface
6. Deactivate/Terminate System Operation
7. Define Procedures/Schedules/Operations
8. Deploy/Retract Appendage
9. Detect Change in State or Condition
10. Gather/Replace Tools/Equipment
11. Implement Procedures/Schedules
12. Inspect/Observe
13. Measure (Scale) Physical Dimensions
14. Position Module
15. Precision Manipulation of Objects
16. Problem Solving/Decision Making/Data Analysis
17. Release/Secure Mechanical Interface
18. Remove Module
19. Remove/Replace Covering
20. Store/Record Element
21. Transport Loaded
22. Transport Unloaded

APPENDIX C

PROJECT ANALYSES

C-1 ANALYSIS OF SPACE PLATFORM MISSIONS

C-2 ANALYSIS OF LIFE SCIENCE MISSIONS

Appendix C-1. SPACE PLATFORM PROJECT (Page 1 of 4)

MISSION	OPERATIONAL SEQUENCES	OPERATIONAL ACTIVITIES
Initial Deployment	Extract from Cargo Bay (Shuttle)	Release Longeron Latches
		Lift SP from Cargo Bay
		Deploy Berthing Mechanism
	Berth	Lower SP to Berthing Position
		Insert Trunnions into Longeron Latches
		Close Longeron Latches
		Mate SP/Orbiter Umbilical
	Deploy Appendages	Deploy Antennas
		Acquire/Autotrack TDRS
		Orbiter to SP Communications
		Elevate Radiator
		Deploy Solar Arrays
		Activate TCS and EPS
		Checkout TCS and EPS
		Orbiter to SP Power and Cooling
		Begin SP CMG Spinup
	Attach Payload	In-Bay Checkout of Payload
		Release Longeron Latches
		Lift Away From Cargo Bay
		Maneuver Payload to Berthing Port
		Berth Payload to Port
		Mate Payload/SP Umbilical
		Payload to SP Power/Cooling
	System Verification Check	Begin Payload Operations
		SP Verification Operation
		End Payload Operations
	Separate	Orbiter/SP to Separation Attitude
		Orbiter to Internal Power/Cooling
		Orbiter to Internal Communications
		Disconnect Orbiter/SP Umbilical
		Inhibit SP CMG's
		Release Longeron Latches
		Lift/Release SP From Orbiter
		Enable SP CMG's
		Orbiter/SP Sep'n Burn Sequence
Payload Reconfiguration	Close Proximity Operations	Retract SP Solar Arrays to 10%
		Retract SP Radiator
		Orbiter Approach to 200 Feet
		Verify SP OK for Docking
		Orbiter Approach to 40 Feet
	Berth	Inhibit Orbiter PRCS
		Inhibit Orbiter VRCS and SP CMG's
		Lower SP to Berthing Position
		Insert Trunnions into Longeron Latches
		Close Longeron Latches
		Mate Orbiter/SP Umbilical
		Extend SP Solar Arrays to 100%
		Extend SP Radiator
		Orbiter to SP TDRS Comm
		Orbiter to SP Power/Cooling
		Activate SP CMG's
	Payload Exchange	Payload to Internal Power/Cooling
		Disconnect Payload/PS Umbilical
		Unberth Payload
		Transfer to Storage Port
		Berth on Storage Port
		In-Bay Checkout of Payload

Appendix C-1. SPACE PLATFORM PROJECT (Page 2 of 4)

MISSION	OPERATIONAL SEQUENCES	OPERATIONAL ACTIVITIES
		Release Longeron Latches Lift Away From Cargo Bay Maneuver Payload to Berthing Port Berth Payload to Port Mate Payload SP Umbilical Payload to SP Power/Cooling Payload Checkout
	Stow Old Payload	Unberth Payload Transfer to Cargo Bay Insert Trunnions into Longeron Latches Close Longeron Latches
	Separate	Orbiter/SP to Sep'n Attitude Orbiter to Internal Power/Cooling Orbiter to Internal TDRS Comm Disconnect Orbiter/SP Umbilical Inhibit SP CMG's Release Longeron Latches Lift/Release SP From Orbiter Enable SP CMG's Orbiter/SP Sep'n Burn Sequence
Maintenance	Close Proximity Operations	See P/L Reconfiguration
	Berth	See P/L Reconfiguration
	Module Exchange	Pre-Maintenance Activities Gather Required Tools Maneuver to Maintenance Location Gain Access to Old Module Disconnect Electrical Connectors Undo mechanical attachment Remove Old Module Transport Old Module to Cargo Bay Attach Old Module to Carrier Remove New Module From Carrier Transport New Module to Maintenance Location Install new Module in Mounting Position Secure Mechanical Attachment Connect Electrical Connectors Replace Access Coverings Transport to Cargo Bay Replace Tools Post Maintenance Activities System Verification
	Separate	See P/L Reconfiguration
Evolutionary Growth	Close Proximity Operations	See P/L Reconfiguration
	Berth	See P/L Reconfiguration
	Module Installation	Gather Tools Maneuver to Module Spares Carrier Remove New Solar Array Wing From Carrier Transport to Storage Port Berth to Storage Port Maneuver to Starboard Solar Array Wing Disconnect Electrical Connectors Undo Mechanical Fasteners Remove Old Solar Array Wing Transport Old S/A Wing to Spares Carrier Attach Old S/A Wing to Carrier Maneuver to Storage Port

Appendix C-1. SPACE PLATFORM PROJECT (Page 3 of 4)

MISSION	OPERATIONAL SEQUENCES	OPERATIONAL ACTIVITIES
		Remove New S/A Wing Transport New S/A Wing to Installation Position Install S/A Wing Secure Mechanical Attachments Connect Electrical Connectors Maneuver to Spares Carrier Remove Battery Charging Pack Transport to Installation Position Gain Access For Module Installations Install Battery Chargers in Mounting Positions Secure Mechanical Attachments Connect Electrical Connectors Maneuver to Spares Carrier Remove Battery Regulator Pack Transport to Installation Position Install Battery Regulators in Mounting Positions Secure Mechanical Attachments Connect Electrical Connectors Maneuver to Spares Carrier Remove Battery Pack Transport to Installation Position Install Batteries in Mounting Positions Secure Mechanical Attachments Connect Electrical Connectors Replace Access Coverings Maneuver to Spares Carrier Remove New S/A Wing From Carrier Transport to Storage Port Berth to Storage Port Maneuver to Port Side S/A Wing Disconnect Electrical Connectors Undo Mechancial Fasteners Remove Old S/A Wing Transport Old S/A Wing to Spares Carrier Attach Old S/A Wing to Carrier Maneuver to Storage Port Remove New S/A Wing Transport New S/A Wing to Installation Position Install S/A Wing Secure Mechanical Attachments Connect Electrical Connectors Transport to Cargo Bay Replace Tools System Verification Check
	Separate	See P/L Reconfiguration
Mission Free-Flyer Ops	Capture Data	Receive and Count Blocks Block Error Check Deblock and Mass Store Transmit to Preprocessor
	Preprocess Data	Receive Data and Store Reverse Tape Recorder Data and Prepare to Batch Extract Data and Establish Observation Sets Correlate and Append Ancillary Data Archive and Transmit to User or Processing Facility

Appendix C-1. SPACE PLATFORM PROJECT (Page 4 of 4)

MISSION	OPERATIONAL SEQUENCES	OPERATIONAL ACTIVITIES
	Analyze Observations (Real Time)	Buffer I/O Display Data Enhance Data Analyze Data
	Calibration	Instrument Radiometric Correction Instrument Geometric Correction
	Locate Observations	Platform Pointing Corrections Payload Pointing Corrections
	Analyze Health and Safety (O/L)	Playback Data Decommutate and Limit Check Extract H&S Subset and Scale Output and Display Processed Data Hard Copy and Plot Data
Plan Mission	Define Instrument Timeline & Command	Define Payload Timeline, Commands & Pointing Profile Define Platform Housekeeping & Science Support Commands & Timeline
	Schedule Maneuvers	Define Instrument Constraints on Maneuvers Define Payload Requirements & Constraints Establish Platform Maneuver Profile Establish Payload Maneuver Profile
	Schedule Observation	Establish Platform Command Timeline Establish Payload Command Timeline Establish Instrument Command Timeline
	Analyze Mission Timeline	Identify Platform Resource Constraint Violations Identify Payload Resource Violations Resolve Conflicts
	Schedule Resources	Define TDRSS Times & Services Define NASCOM Times & Services Confirm Schedules Resolve Conflicts & Changes
	Integrate Commands & Schedules	Develop & Time Correlate Uplink & Real Time Command People Constraint Check Integrated Command Load
	Command TDRSS, Platform, Payload & Instruments	Acquire Communication Links Uplink Memory Loads Perform & Manage Real Time Commanding
	Relay Communication	Provide Links & Services Link WSGT to DCF Acquire SP RF Lock RF Quality Checks & Demodulate Data Block & Forward Data
	Platform C & DH	Encode Payload Data Stream Correlate & Encode Ancillary Data Multiplex & RF Data Decode & Distribute Platform & Payload Command & Command Loads
	Payload C & DH	Synchronize & Encode Sensor Data Extract Quick Look Observation Data Synchronize & Encode H&S Data Tag & Output Data to Payload C & DH Process Instrument Commands & Command Loads

Appendix C-2. LIFE SCIENCES RESEARCH PROGRAM (Page 1 of 6)

MISSION	OPERATIONAL SEQUENCES	OPERATIONAL ACTIVITIES
I. Study Of Bone Demineralization In Zero Gravity	A. Maintain & Monitor Rat Colony	1. Visually inspect rats within habitat a. Make direct visual inspections. b. Inspect video images of rats. 2. Examine displays of habitat environmental parameters. a. Call up environmental data. b. Evaluate data with respect to required ranges. 3. Inspect records of food and water consumption a. Call up records for speciment on CRT. b. Compare records with normal consumption data. 4. Evaluate animals health. 5. Process urine samples a. Remove urine collector b. Measure urine volume and deliver aliquot to container. c. Place container in freezer - check freezer temeprature d. Record data on appearance of urine and sample size.
	B. Measure Mass of Rats	1. Transfer rat from habitat to SMMD a. Remove habitat from holding facility. b Place habitat in workbench. c Open habitat and remove rat d Transfer rat to SMMD module and secure e. Attach restraint module to SMMD. 2 Operate SMMD. a. Activate SMMD. b Read display of rat's mass and record. 3. Return rat to holding facility.
	C Acquire, Process, and Store Rat Blood Sample	1 Acquire blood sample and centrifuge a. Remove rat from habitat at workbench. b. Place rat in restraint unit c Apply tail heater. 2 Acquire blood sample and centrifuge a. Remove blood sample from tail vein b Transfer sample to centrifuge tube. c. Return rat to habitat in holding facility. d. Centrifuge blood samples

MISSION	OPERATIONAL SEQUENCES	OPERATIONAL ACTIVITIES
		3. Store Samples a. Draw off plasma from tubes. b Record volume and transfer to storage tubes c. Store samples in freezer - note freezer temperatures
	D. Sacrifice Rats, Acquire and Store Tissue Samples	1. Prepare rats for dissection. a. Remove rat from habitat in workbench enclosure. b. Return habitat to holding unit. c. Place rat in guillotine restraint system d Guillotine rat. e. Remove rat from guillotine restraint system and secure to dissection board
		2. Dissect rat and remove tissue samples a. Dissect rat and remove samples of interest. b. Remove samples and place in holding containers.
		3. Freeze samples and store. a Transfer samples from saline solution to cryogenic coolant. b. Remove samples from cryogenic freezer and store in freezer. c Discard remains into waste management system.
	E Analyze Blood and Urine Samples	1 Analyze samples a. Remove samples from freezer and thaw b. Transfer samples to analyzer containers. c. Place samples in analyzer and activate d. Operate analyzer. e Examine and record results.
		2 Study results. a. Examine data for internal consistency. b Compare data to normal values c. Compare data to expected changes. d. Make judgments about bone loss in zero gravity. e Log conclusions and discuss with terrestrial P.I 's
		3. Plan subsequent experiments a. Determine if changes warrant alterations in exp protocol. b Determine laboratory support capabilities. c. Plan logistics

MISSION	OPERATIONAL SEQUENCES	OPERATIONAL ACTIVITIES
	F. Perform Histological Analysis	1 Prepare tissue a. Remove tissue and trim for mounting on microtome b. Imbed tissue in paraffin c. Mount tissue block on microtome d. Operate microtome e. Mount tissue slices on microscope slides f. Conduct staining procedure
		2. Examine tissues under microscope a Mount slide on microscope. b. Focus microscope c. Examine tissue for abnormalities. d Photograph views of interest. e. Record findings and discuss with terrestrial P I
		3. Study results a. Examine data fo internal consistency. b. Compare data to normal values. c. Compare data to expected changes. d Make judgments about bone loss in zero gravity e. Log conclusions and discuss with terrestrial P.I 's
		4 Plan subsequent experiments a Determine if changes warrant alterations in exp protocol b. Determine laboratory support capabilities. c Plan logistics
II. Study of Metabolic Work In Zero Gravity In Humans	A Set Up Experiment for Metabolic Experiment	1 Prepare bicycle ergometer a. Remove from storage and assemble. b. Checkout functions and calibrations. c Introduce workload program into ergometer micropocessor.
		2. Set up cardiovascular monitoring system. a. Establish appropriate interconnections among system components. b. Checkout functions, operations, and calibrations
		3. Set up metabolic monitoring system. a Establish appropriate interconnections among system components. b Checkout functions, operations, and caliberations.
	B Prepare Subject for Metabolic Testing	1. Measure mass of subject a. Position subject in body mass measurement device (BMMD) b. Activate and operate BMMD c Read mass from BMMD display and record.

MISSION	OPERATIONAL SEQUENCES	OPERATIONAL ACTIVITIES
		2. Apply sensors to subject. a. Subject electrode locations on subject. b. Prepare and apply electrodes. c. Attach electrode lead system d. Connect lead system and check integrity of assemblies.
		3 Fasten, adjust, and checkout respiratory mask and valve. a. Position mask and fasten head straps b. Adjust mask to facial anatomy of subject. c Attach valve and hose to mask. d Check mask for flow and leaks.
	C. Monitor Metabolic Work	1. Monitor cardiovascular function. a Check heart rate display. b. Evaluate heart rate with regard to work load. c. Examine ECG waveform d. Identify ECG abnormalities e. Actuate oscilloscope camera. f. Check operation of strip chart recorder g Assess status of subject
		2 Monitor metabolic parameters. a Monitor O_2 consumption/CO_2 production b Evaluate metabolic rate with regard to workload c. Assess status of subject's physical conditioning d. Check computation of PQ e Examine and evaluate operation of X-Y plotter.
		3 Terminate metabolic work test a Monitor physiological parameters during recovery period b. Remove electrodes/sensors from subject c. Disassemble and store experiment equipment d. Collect experiment records.
	D Analyze Metabolic Experiment	1 Reduce experiment data. a. Enter data from experiment records onto data forms b Calculate derived values and correlations c Evaluate effects of zero gravity on metabolic work d. Record conclusions and discuss with terrestrial P I 's
		2 Plan subsequent experiments a Determine if changes warrant alterations in exp. protocol. b Determine laboratory support capabilities. c Plan logistics

MISSION	OPERATIONAL SEQUENCES	OPERATIONAL ACTIVITIES
III. Study Of Vestibular Function In Zero Gravity	A Set Up Equipment for Vestibular Experiment	1. Assemble VRF and prerpare for operation a. Assemble shaft arms and drive system. b. Attach specimen modules. c. Test operation of VRF system.
		2 Set up electrophysiological measurement system a. Establish appropriate inter-connections. b. Checkout functions, operations, and calibrations.
		3 Prepare specimen for test. a Transfer habitat from holding facility to workbench enclosure. b. Remove rat form habitat and anesthetize c. Examine status of implanted electrodes. d. Apply surface electrodes e Check signal characteristics f. Install rat in VRF module g Attach specimen module to VRF h. Recheck electrophysiological signals
	B Conduct Vestibular Function Exp	1 Conduct prelim experiment activities a. Collect baseline (non-rotational) data b Program operational parameters into VRF microprocessor c Check module environmental parameters
		2. Initiate experiment. a Activate VRF rotational and gravitational vector programs. b Check operation of monitoring system c. Display physiological parameters. d Evaluate physiological variables with respect to acceleration vectors.
		3. Monitor experiment procedure. a. Monitor environmental displays. b Monitor VRF operations c Monitor electrophysiological displays
		4 Terminate experiment a Stop VRF rotation b Continue monitoring electrophysio-logical displays c Transfer module to general purpose workbench d Disconnect electrode leads and specimen restraint system e Transfer specimen to habitat and return to holding facility

Appendix C-2. LIFE SCIENCES RESEARCH PROGRAM (Page 6 of 6)

MISSION	OPERATIONAL SCIENCES	OPERATIONAL ACTIVITIES
	C Analyze Vestibular Exp Data	1. Reduce experiment data a. Enter data on data forms. b. Calculate derived values and correlations. c. Evaluate effects of rotation on physiological variables d. Record conclusions and discuss with terrestrial P.I.'s. 2. Plan subsequent experiments. a Determine if changes warrant alteration in exp. protocol b Determine laboratory support capabilities. c. Plan logistics.

APPENDIX D

ACTIVITY TIMELINE PROFILES AND DATA SHEETS

FOR 37 GENERIC ACTIVITIES

APPENDIX D

Timeline Profiles

This appendix contains the timeline profiles for each of the 37 Generic Space Activities derived in Task 2.1. For each activity, a timeline range bar represents the typical range of times that can be expected in accomplishing the specific task in each man-machine category. For each time range, one or more information sources are referenced. The symbology as described in Section 3.2 of the report designates the general nature of the source. The information sources that are referenced in the timeline profiles correspond to the following:

(1) McDonnell Douglas Astronautics Company, Alternative System Design Concept Study (Space Plat~~form/Power~~ System), Contract NAS8-33955, DR Nos. 1-16, July 1982.

(2) Space Platform Ground System Study - Final Report, 7/21/82, Ford Aerospace and Communications Corporation (Subcontract to MDAC under NAS8-33955).

(3) Space Station Program Description Document - Book #6, Appendix B, Operations Studies, Second Level White Pages, 8/83, Space Station Operations Working Group, NASA-KSC.

(4) National Aeronautics and Space Administration, Skylab Mission Sequence Evaluation, TMX-64816, March 1974.

(5) Space Station - Vol. III, Book 3, 48 Hr. Analysis, MDC G0634, 7/70, Contract NAS8-25140.

(6) Space Station - Crew Operations Definitions, MDC G0645, 8/70, Contract NAS8-25140.

(7) Space Maintenance and Contingency Operations Simulation Neutral Buoyancy Testing (NB-51) - Final Report, MDC H0190, MDAC-HB, May 1983.

(8) McDonnell Douglas Astronautics Company Engineering Estimate.

(9) National Aeronautics and Space Administration, Johnson Space Center, Mission Planning and Analysis Division, The 25-Kilowatt Power System - Baseline Reference Mission, JSC 17066, February 1981.

(10) General Dynamics, Definition of TDMs for Early Space Station - Orbit Transfer Vehicle Servicing, Vol. 2 - Technical Report, Contract NAS8-35039, June 1983.

(11) Spacelab 1/STS 9 Operations Debriefing and Flight Review.

(12) Similar task has been demonstrated/observed in some other actual space flight operation.

(13) National Aeronautics and Space Administration, Marshall Space Flight Center, Analysis of Large Space Structures Assembly - Man-Machine Assembly Analysis, Contractor Report No. 3751, NAS8-32989, December 1983.

(14) Ewald Heer (Editor), Remotely Manned Systems - Exploration and Operation in Space, California Institute of Technology, 1973.

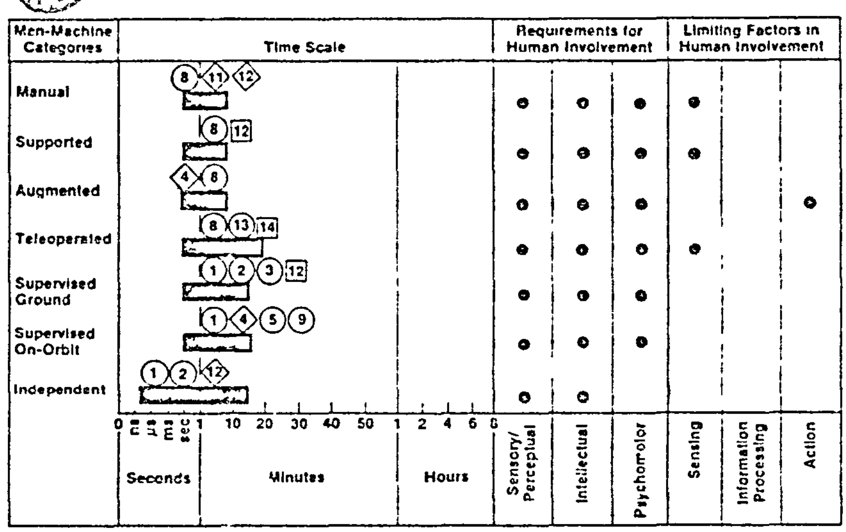
VGM425

ACTIVITY TIMELINE GROUNDRULES

- Range of Times Derived From Analyses of Specific Tasks
  - Similar Task With Actual On-Orbit Performance
  - Similar Task Performed in a Space Simulation
  - Engineering Estimate Based on Design or Operational Experience
- Activities Requiring Direct Human Involvement for Accomplishment Eliminate Supervised/Independent Options
- Manual Operations Limited to 50 Minutes Based on Fatigue Levels and Attention Span Limits
- "Limiting Factors" Establish Rationale for Man-Machine Category Allocations

VGS985

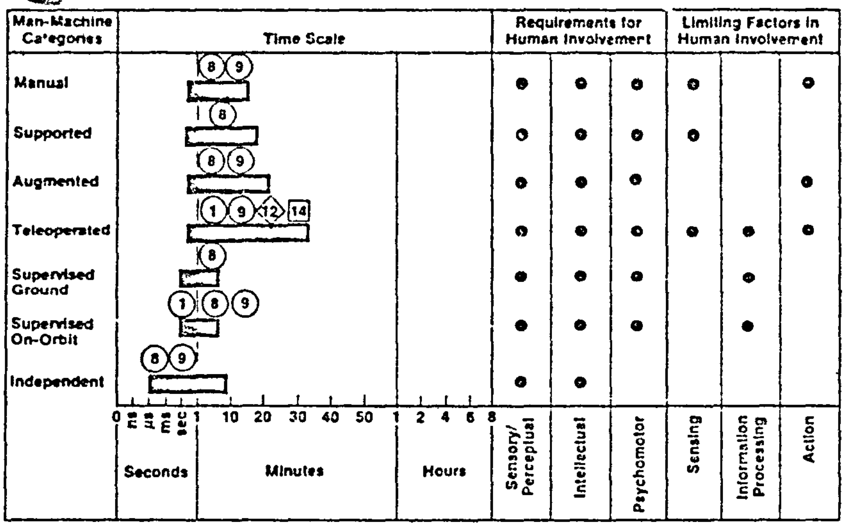
ACTIVATE/INITIATE SYSTEM OPERATION



MCDONNELL DOUGLAS

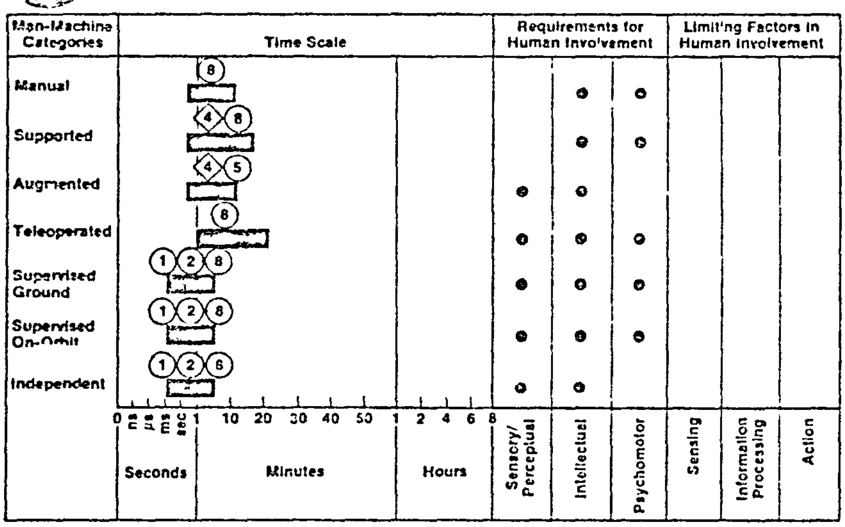
ADJUST/ALIGN ELEMENTS

VGS987



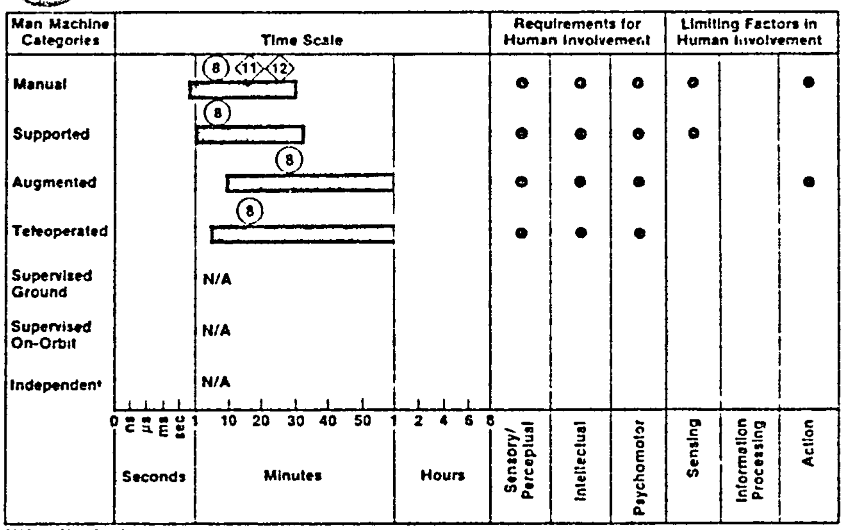
ALLOCATE/ASSIGN/DISTRIBUTE

VGS988



VGS989

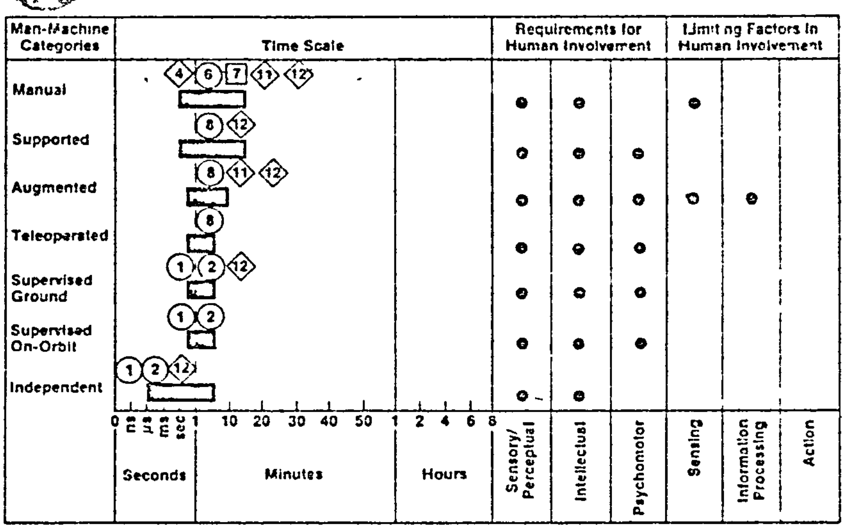
APPLY/REMOVE BIOMEDICAL SENSOR



N/A — Not Applicable

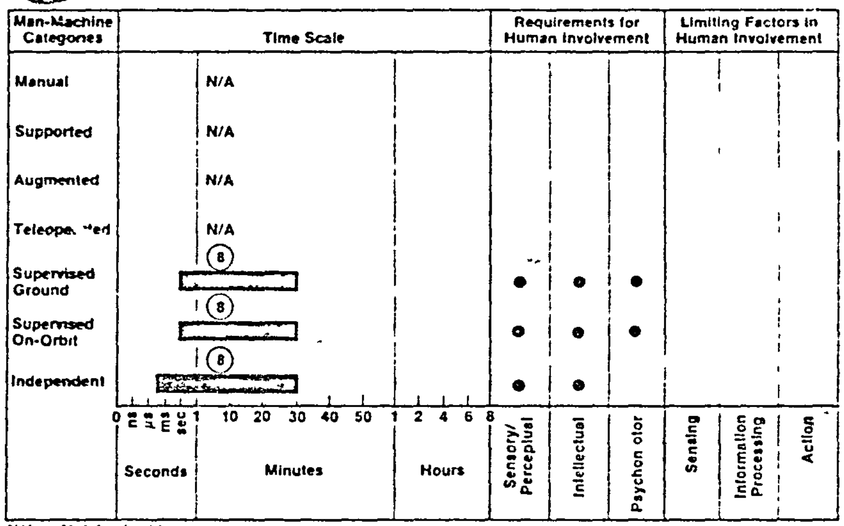
VGS990

COMMUNICATE INFORMATION



VGS991

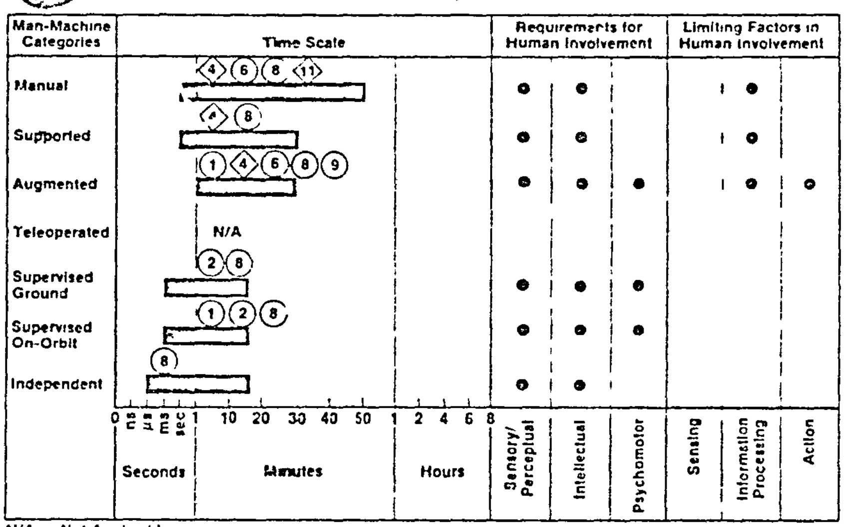
COMPENSATORY TRACKING



N/A — Not Applicable

VGS992

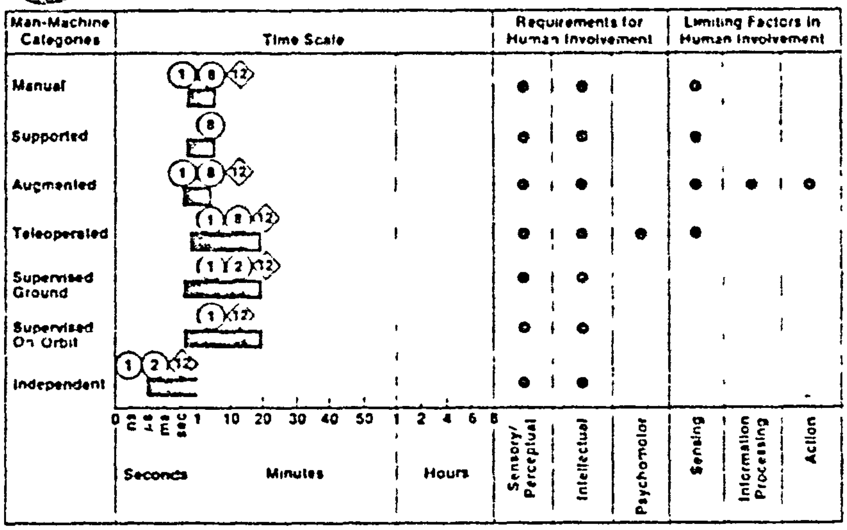
COMPUTE DATA



N/A — Not Applicable

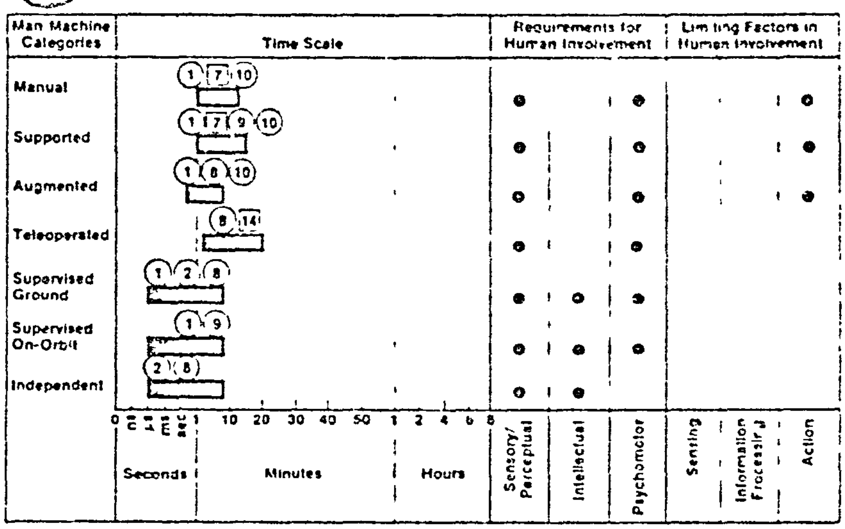
CONFIRM/VERIFY PROCEDURES/ SCHEDULES/OPERATIONS

VGS993



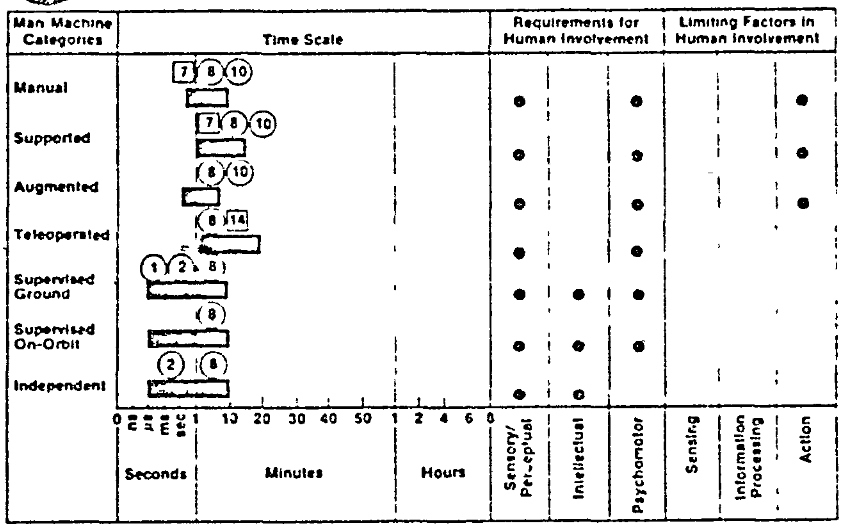
VGS994

CONNECT/DISCONNECT ELECTRICAL INTERFACE



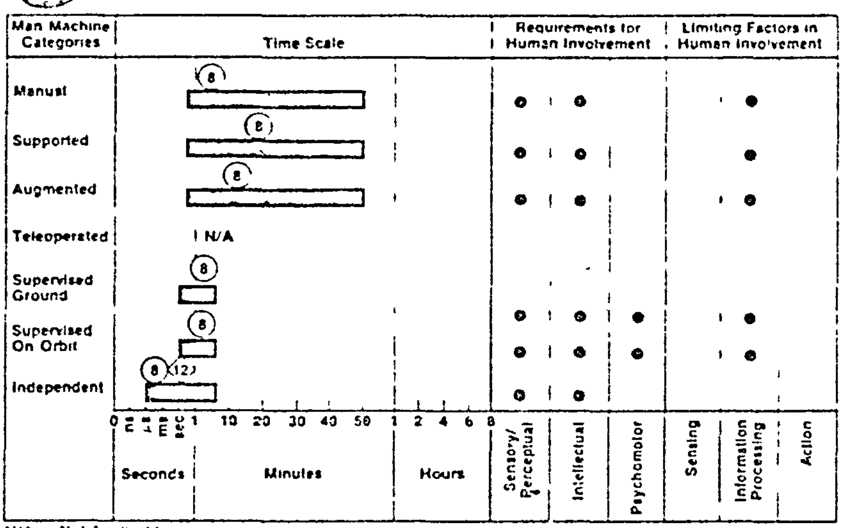
CONNECT/DISCONNECT FLUID INTERFACE

VG5995



CORRELATE DATA

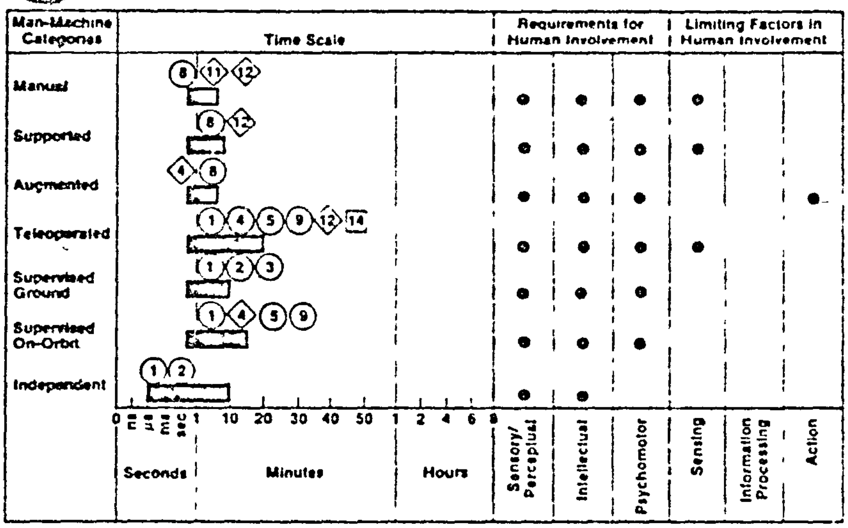
VG5996



N/A — Not Applicable

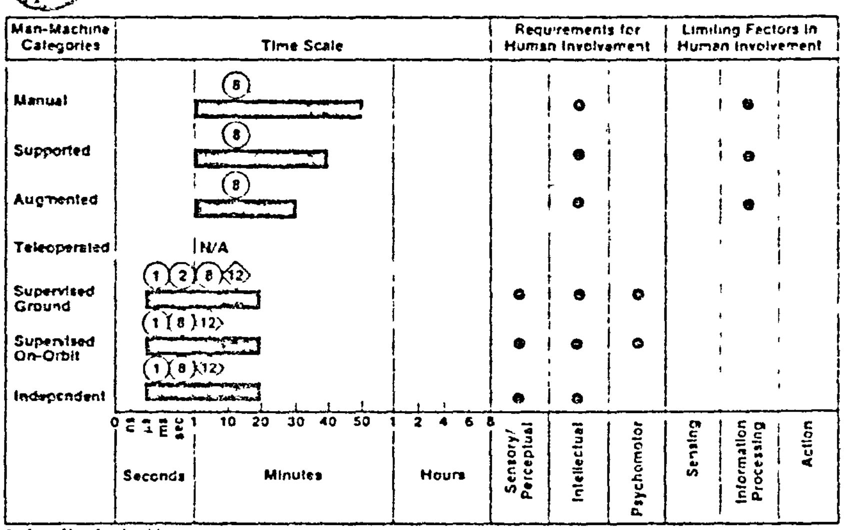
DEACTIVATE/TERMINATE SYSTEM OPERATION

VGS997



DECODE/ENCODE DATA

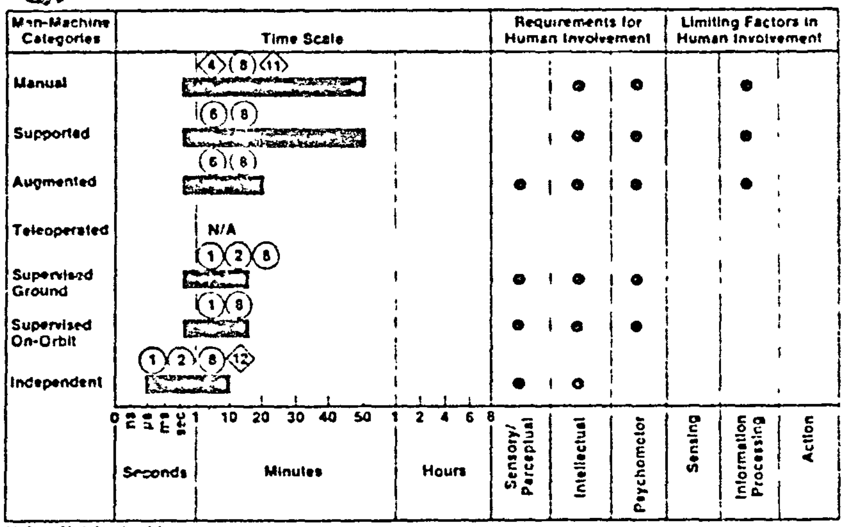
VGS998



N/A — Not Applicable

DEFINE PROCEDURES/ SCHEDULES/OPERATIONS

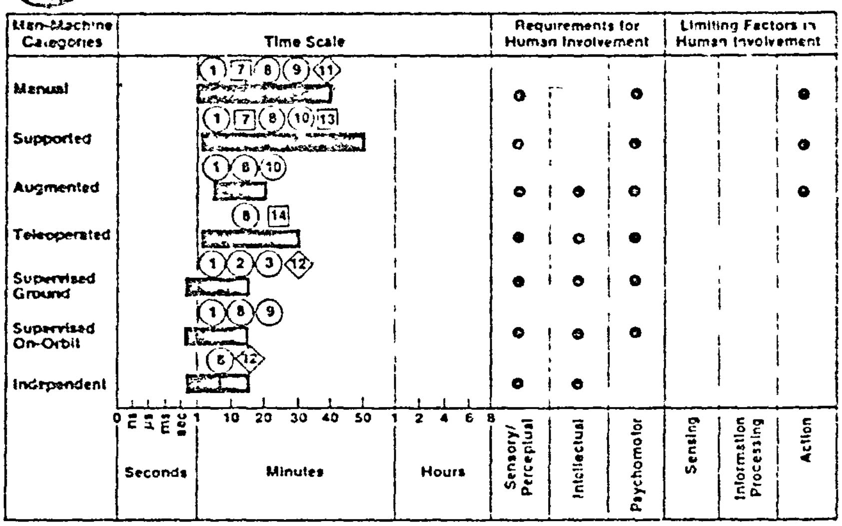
VG5999



N/A — Not Applicable

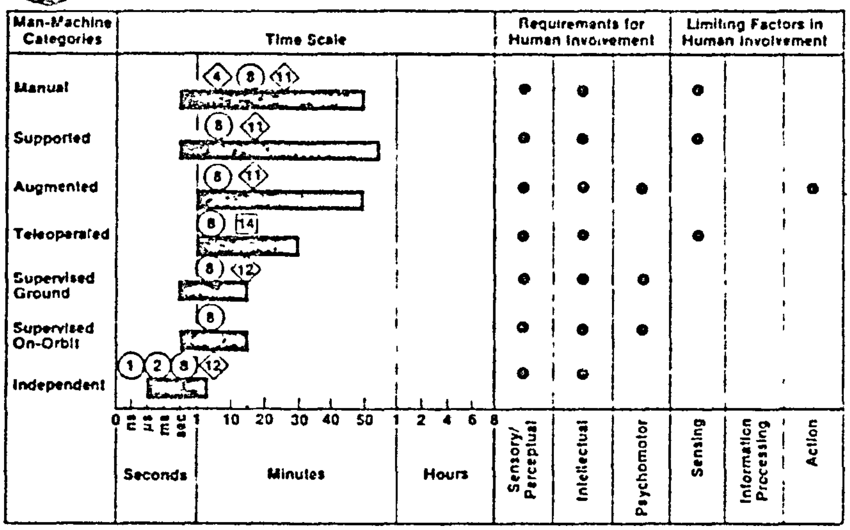
DEPLOY/RETRACT APPENDAGE

VGT000



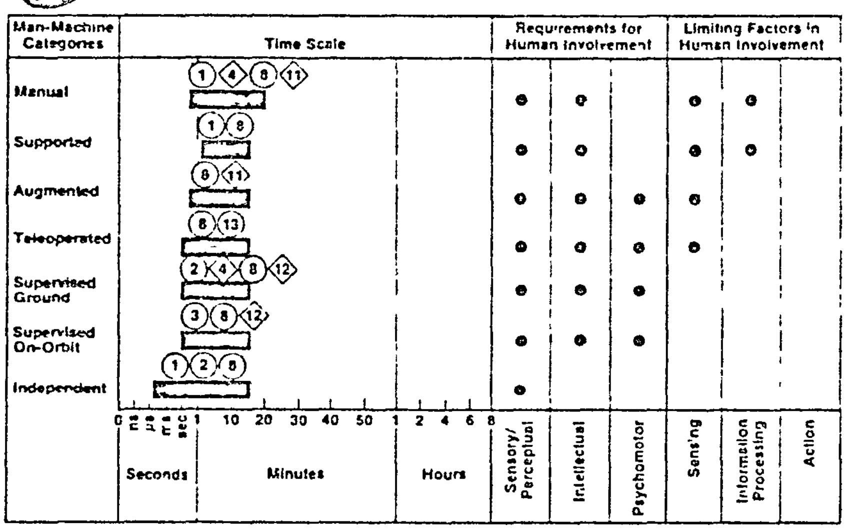
DETECT CHANGE IN STATE OR CONDITION

VGT001



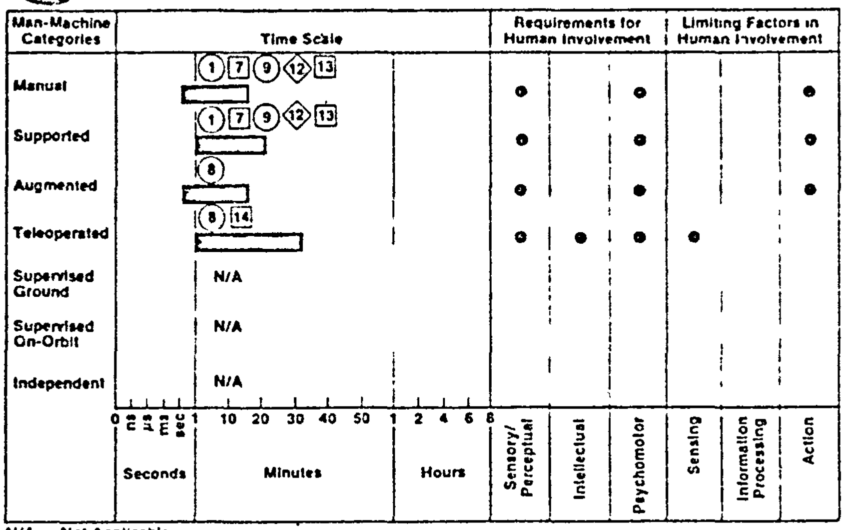
DISPLAY DATA

VGT002



GATHER/REPLACE TOOLS/EQUIPMENT

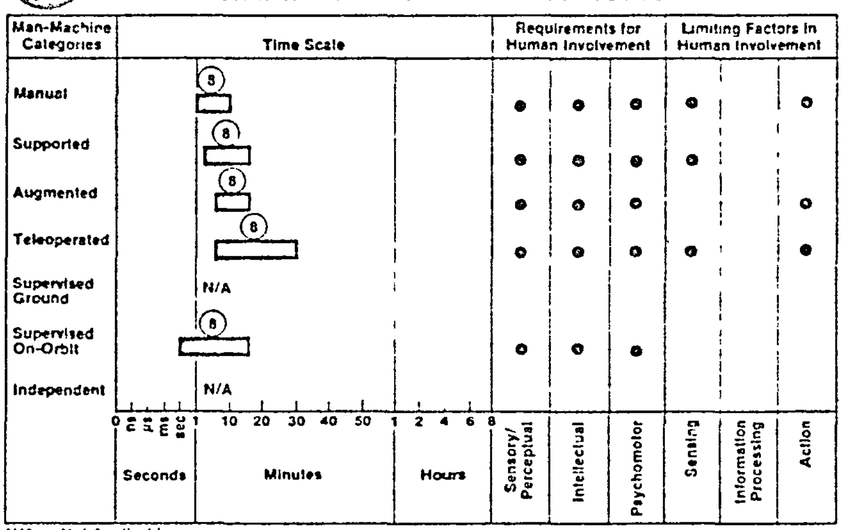
VGT003



N/A — Not Applicable

VGT004

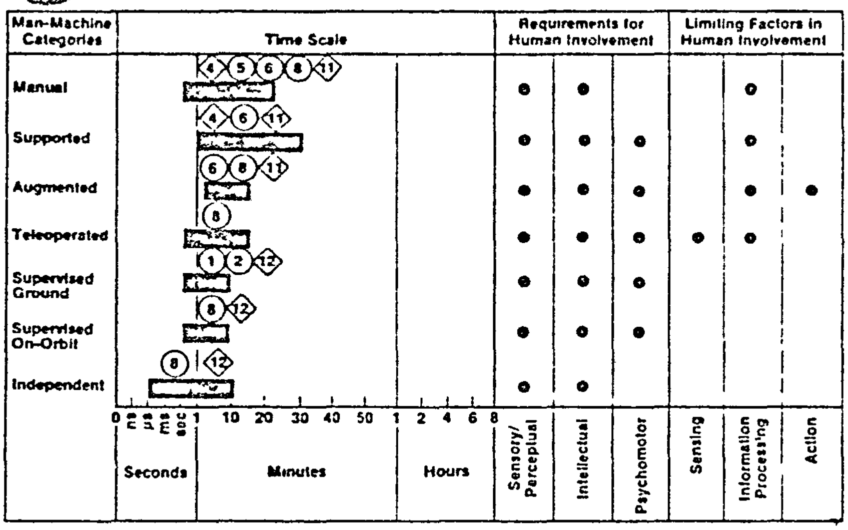
HANDLE/INSPECT/ EXAMINE LIVING ORGANISMS



N/A — Not Applicable

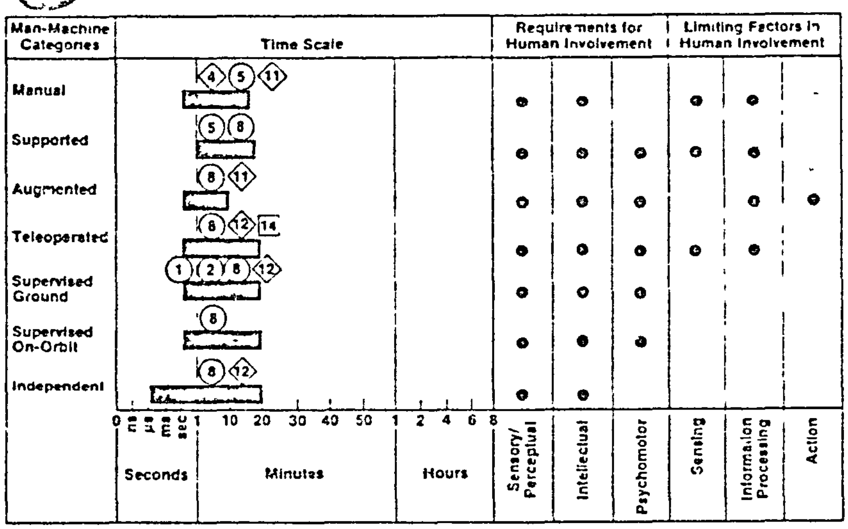
IMPLEMENT PROCEDURES/SCHEDULES

VGT005



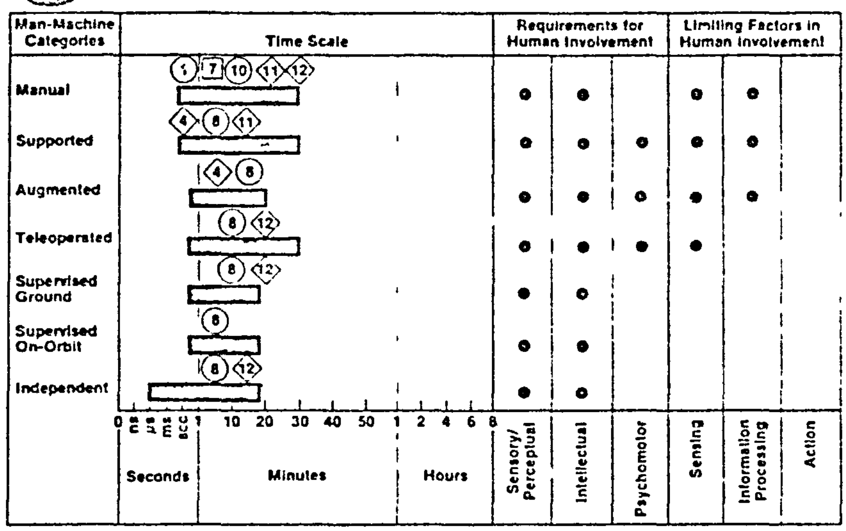
INFORMATION PROCESSING

VGT006



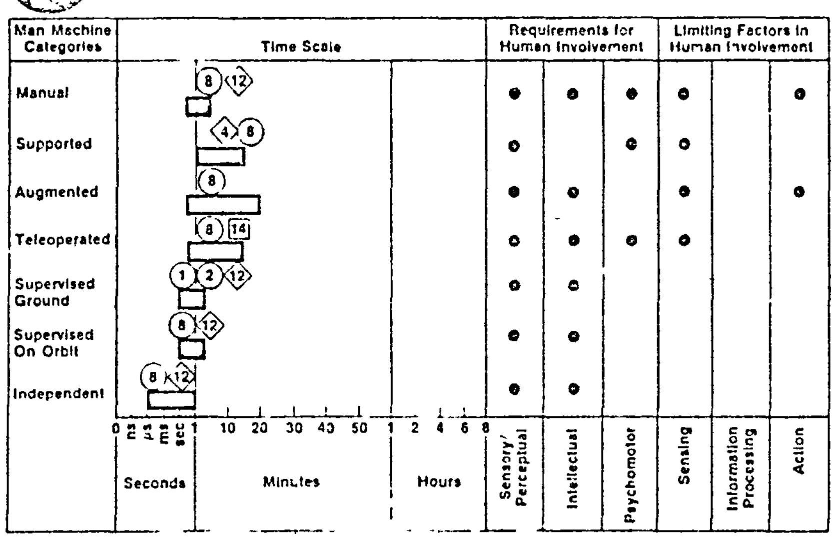
INSPECT/OBSERVE

VGT007



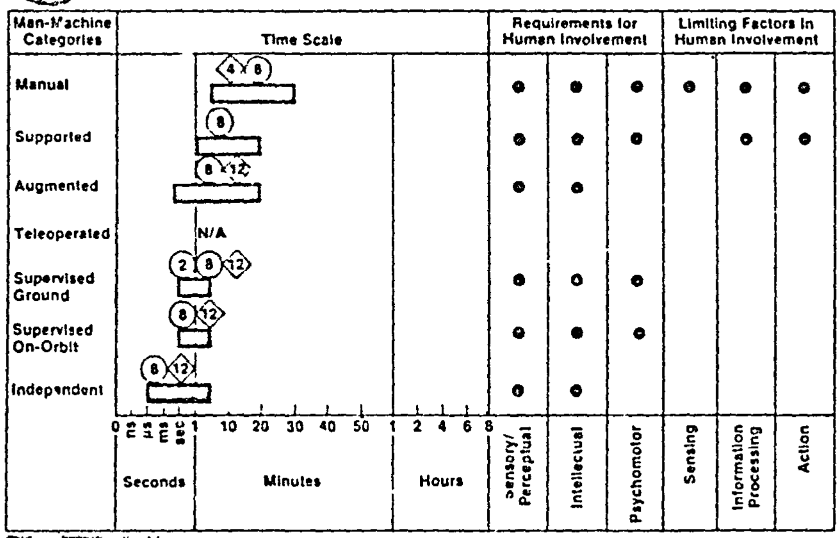
MEASURE (SCALE) PHYSICAL DIMENSIONS

VGT008



VGT009

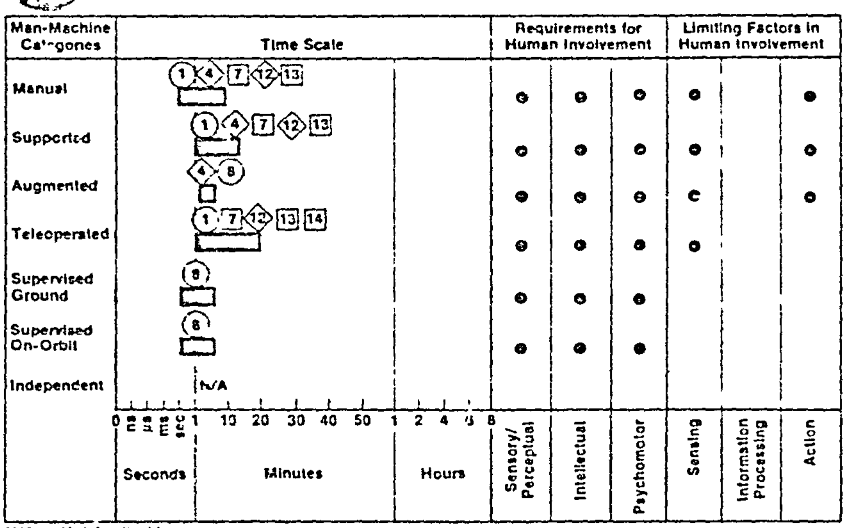
PLOT DATA



N/A — [redacted]plicable

VGT010

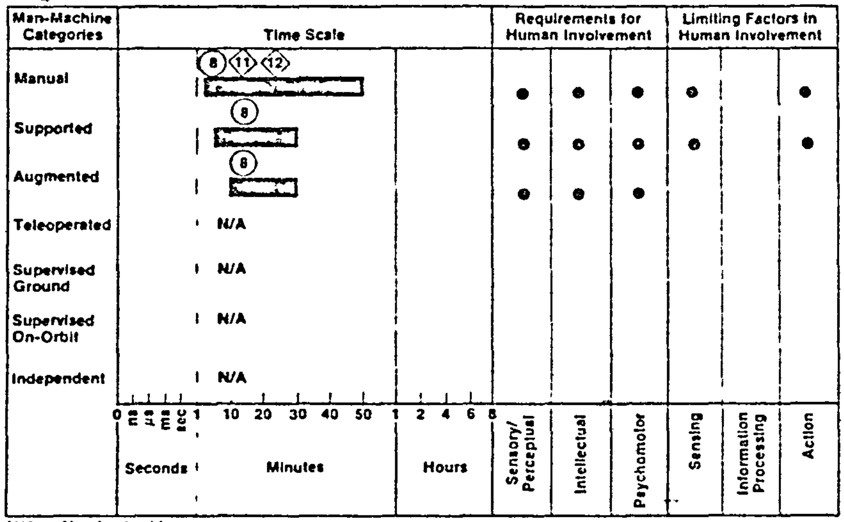
POSITION MODULE



N/A — Not Applicable

PRECISION MANIPULATION OF OBJECTS

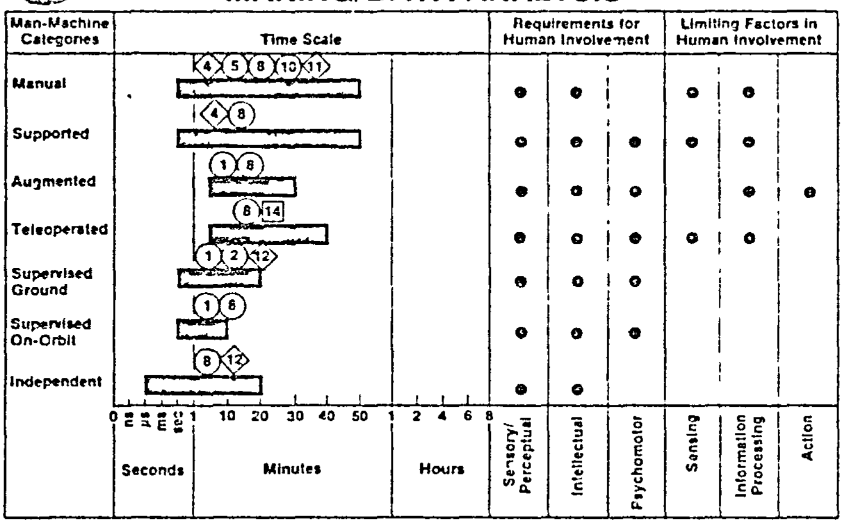
VGT011



N/A — Not Applicable

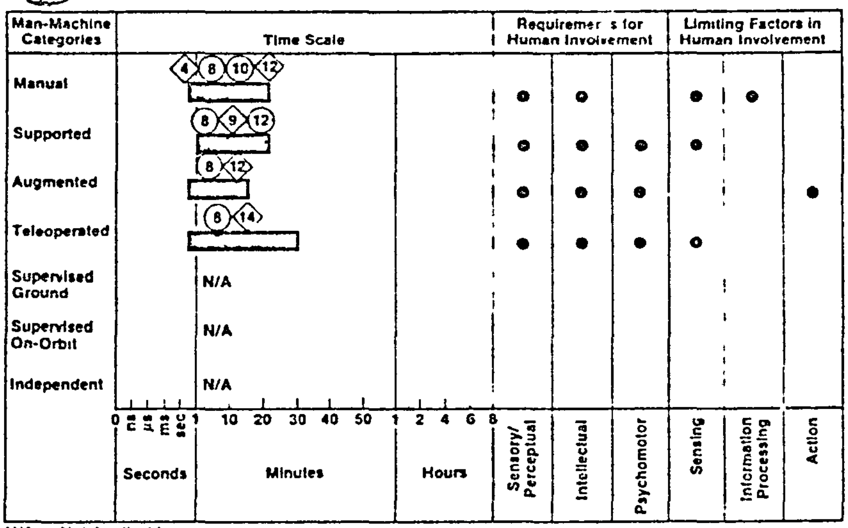
PROBLEM SOLVING/DECISION MAKING/DATA ANALYSIS

VGT012



VGT013

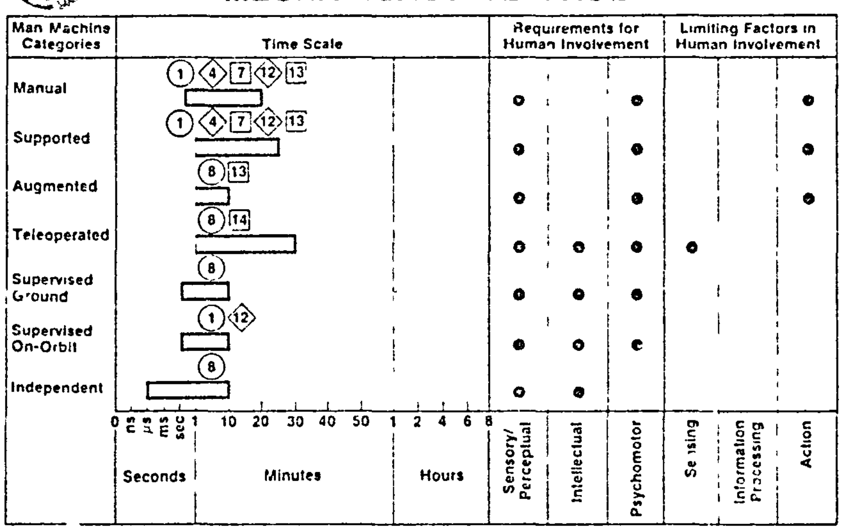
PURSUIT TRACKING



N/A — Not Applicable

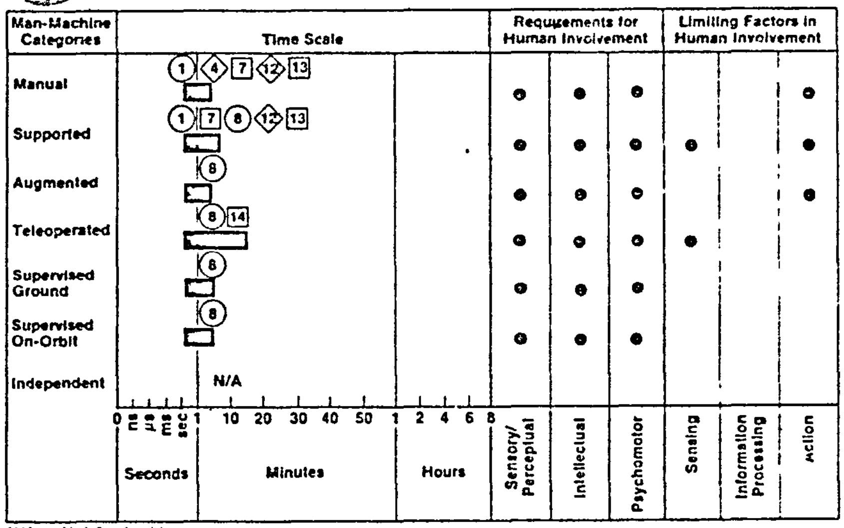
RELEASE/SECURE MECHANICAL INTERFACE

VGT014



VGT015

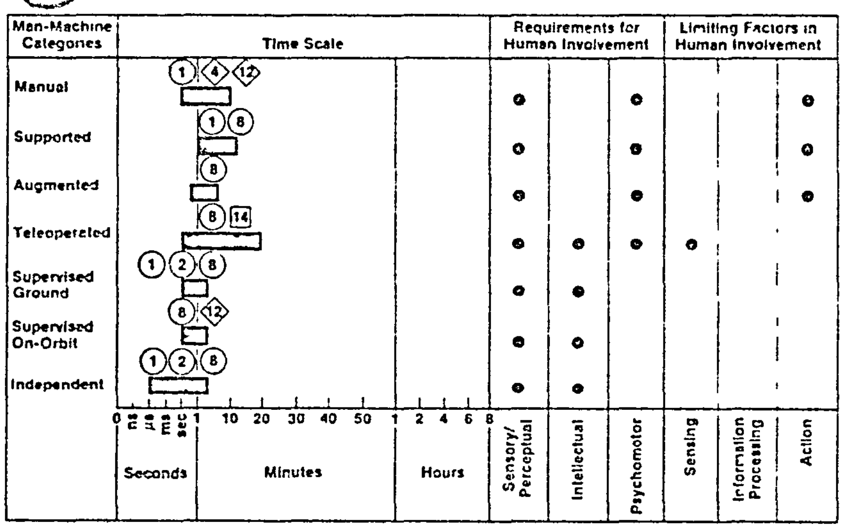
REMOVE MODULE



N/A — Not Applicable

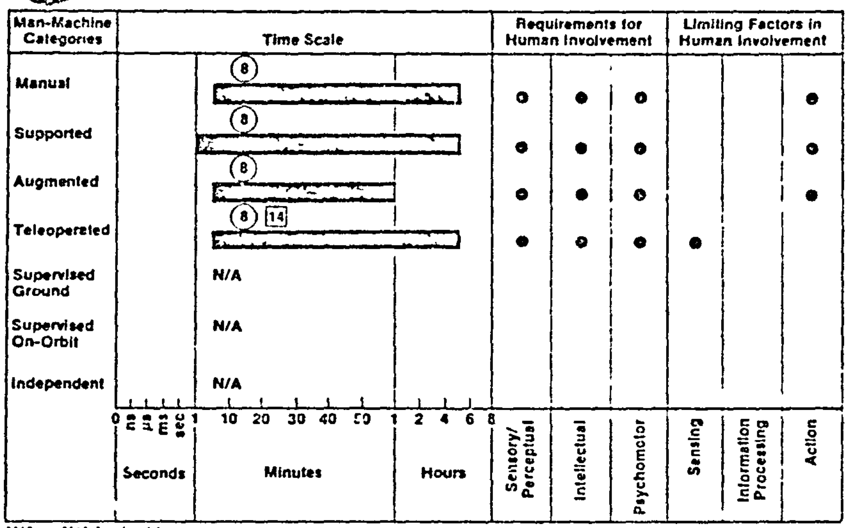
VGT016

REMOVE/REPLACE COVERING



VGT017

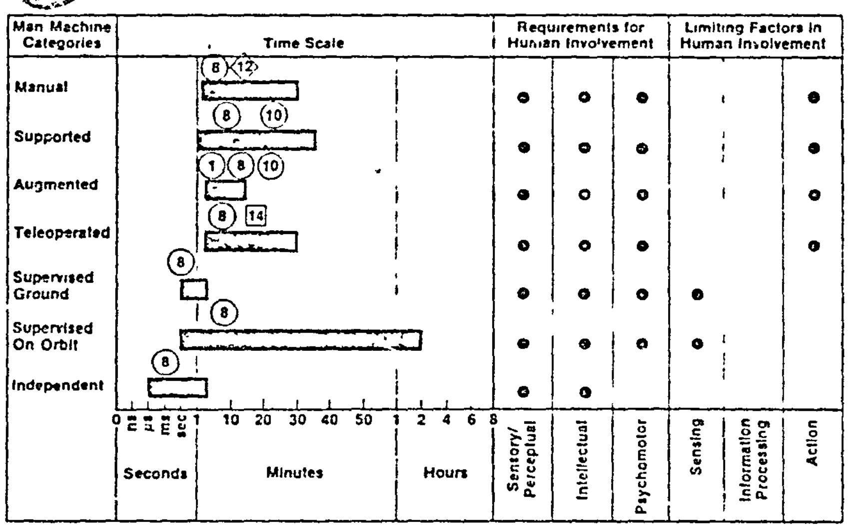
REPLACE/CLEAN SURFACE COATINGS



N/A — Not Applicable

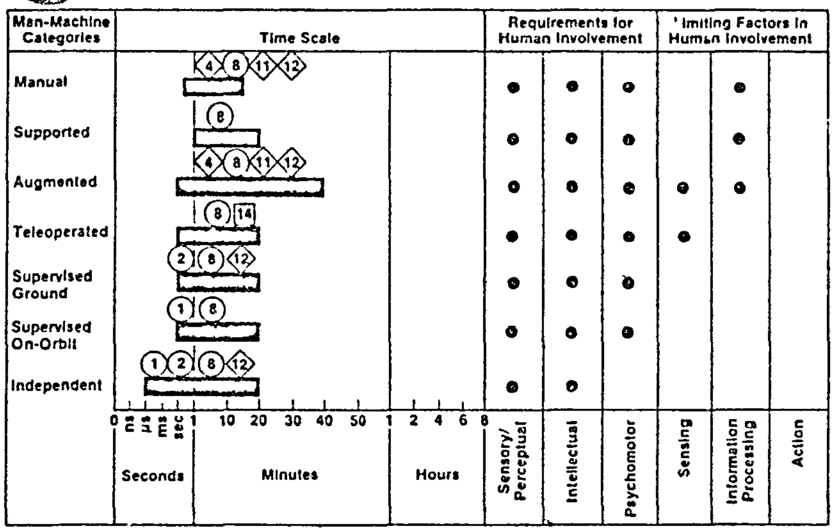
VGT018

REPLENISH MATERIALS



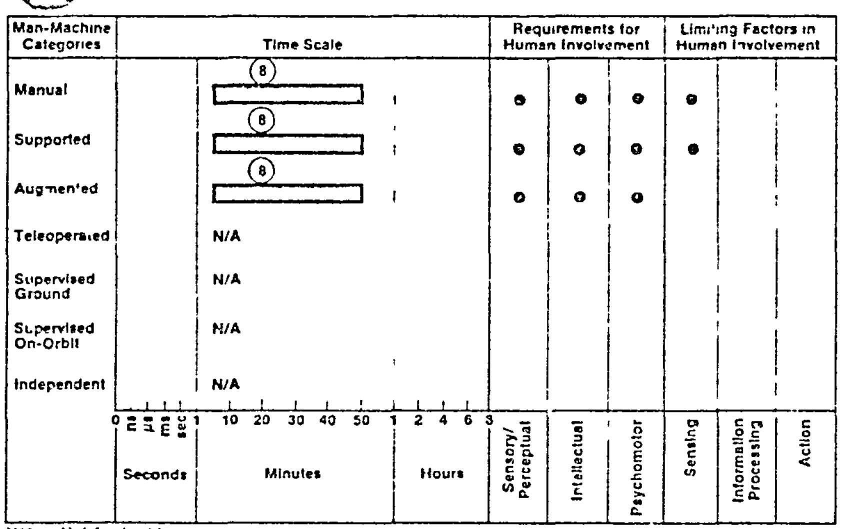
VGT019

STORE/RECORD ELEMENT



VGT020

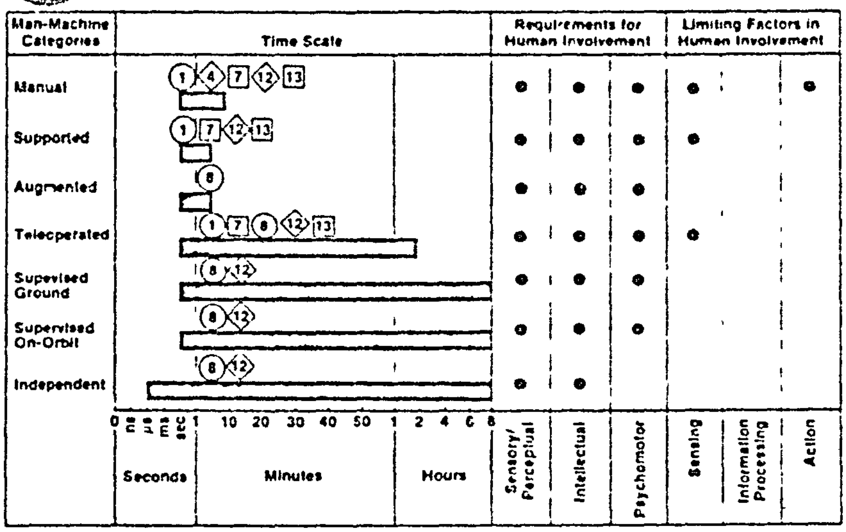
SURGICAL MANIPULATIONS



N/A — Not Applicable

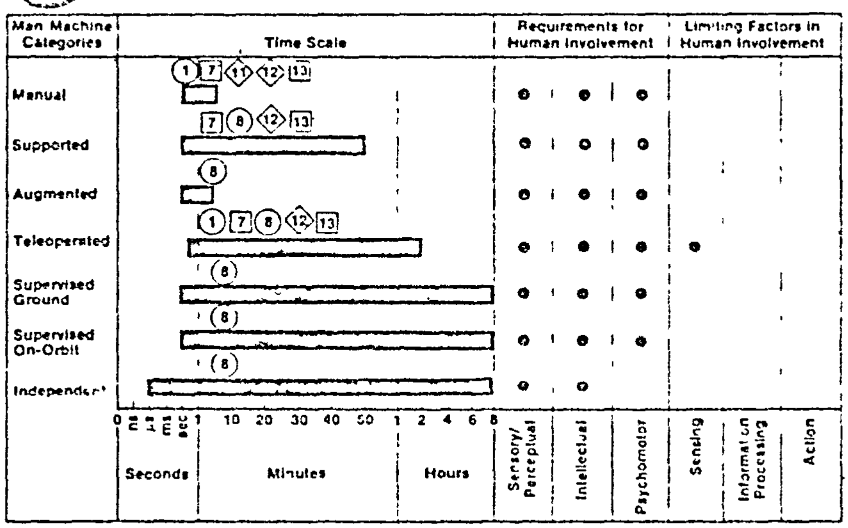
TRANSPORT LOADED

VGT021



TRANSPORT UNLOADED

VGT022



APPENDIX E

SUPPORT EQUIPMENT

REQUIREMENTS FOR

37 GENERIC ACTIVITIES

Table E-1

SUPPORT EQUIPMENT LIST FOR COSTING VARIOUS MAN-MACHINE MODES

A.	Facilities
A1.	Space Station Facility
A2.	Ground Control Center, Baseline System
A3.	Payload Control Center, Baseline System
A4.	Data Handling Facility, Baseline System
A5.	Tracking and Data Relay Satellite System (TDRSS)
A6.	Unmanned Platform Basic Resources
B.	EVA Support Items
B1.	Extravehicular Mobility Unit (EMU)
B2.	Manned Maneuvering Unit (MMU)
B3.	Remote Manipulator System (RMS)
C.	Tool Kits and Mechanical Support Equipment
C1.	Power Tool, Portable
C2.	Tool Kits, Manual
C3.	Gas Recharge Kit
C4.	Fluid Recharge Kit
C5.	Test Set, Alignment/Calibration, Portable
C6.	Test Set, Electrical Checkout
C7.	Surface Coating/Refurbishment Apparatus
C8.	Support Equipment, Experiment Specific - Category A
C9.	Support Equipment, Experiment Specific - Category B
C10.	Support Equipment, Experiment Specific - Category C
C11.	Support Equipment, Experiment Specific - Category D
C12.	Cherry Picker with Work Platform (RMS)
C13.	Restraints to Support Manned Activities
C14.	Life Sciences Experiments Tool Kits

Table E-1

SUPPORT EQUIPMENT LIST FOR COSTING VARIOUS MAN-MACHINE MODES (Continued)

D. Command, Control, Communication, and Data Management Equipment

D1. Control/Display for Remote Gimbals
D2. Control/Display for Remote Cameras (TV and Photo)
D3. Automatic Adjustment for Control of Remote Equipment
D4. Voice Intercommunication
D5. Control and Display Activation and Monitoring Equipment, Keyboard
D6. Hardware for Accepting Remote Commands
D7. Display and Software for Record Keeping, Procedures, Schedules, and Maintenance
D8. Computer Programmed for Command and Control of a Specific Function/Task by Artificial Intelligence
D9. Encode/Decode Data Equipment
D10. Data Computation and Reduction Equipment
D11. Input/Output Data Buffer Equipment
D12. Central Timing Unit
D13. NSSC Interface Management Unit
D14. Remote Units
D15. CDMS Central Unit
D16. High-Rate Recorder
D17. Low-Rate Recorder
D18. NSSC-II Computer
D19. Ku-Band Communication Equipment
D20. S-Band Communication Equipment
D21. Low-Gain Antennas
D22. RF Transfer Switch
D23. Support Instrumentation/Sensor Equipment
D24. Telemetry Unit
D25. Payload Command and Data Acquisition Unit

Table E-1

SUPPORT EQUIPMENT LIST FOR COSTING VARIOUS MAN-MACHINE MODES (Continued)

E.	Orbital Mobility Systems
E1.	Orbital Maneuvering Vehicle (OMV)
E2.	Orbital Transfer Vehicle (OTV)
E3.	Telepresence Manipulator System (TMS)
F.	Operating Systems Software
F1.	User Interface
F2.	Facility Readiness Test (Integration)
F3.	Dynamic Scenario Profile Generation
F4.	Command Generation
F5.	Telemetry Data Handling
F6.	Input/Output
F7.	Test Data Generation
F8.	Data Base Generation/Maintenance
F9.	Data Reduction
F10.	Support Software
F11.	Software for Command and Control Hardware Controlled from a Remote Ground or Orbital-Based Work Station
F12.	Software for Computer Programmed for Command and Control of a Specific Function/Task by Artificial Intelligence

SUPPORT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 1	CATEGORIES OF MAN-MACHINE INTERACTIONS						
					SUPERVISED		
ACTIVATE/INITIATE SYSTEM OPERATION	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	GROUND	ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED (SEE TABLE E-1)						
I V A	A1 C8	A1 C8 C13	A1 C9 C13	A1 C10 D5 D6	A2 A5 A6 D5 D6 F11	A1 D5 D6 F11	A2 A3 A4 A5 A6 D3 D6 D7 D8,F12*
E V A	A1 B1 C8 C13	A1 B1 C8 C13	A1 B1 C9 C13				

EXAMPLE - Activate Camera/T.V. Image Gathering Equipment

MANUAL - 35 mm Camera
SUPPORTED - 35mm Camera with Auto Advance
AUGMENTED - 35mm Camera with Auto Timing Sequence
TELEOPERATED - RMS TV Camera
SUPERVISED GROUND - TV Camera
SUPERVISED ON-ORBIT - TV Camera
INDEPENDENT - Satellite Image Equipment

*Considered as one item of support equipment
D8 - Computer Hardware
F12 - Associated Software

SUPPORT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 2	CATEGORIES OF MAN-MACHINE INTERACTIONS						
					SUPERVISED		
ADJUST/ALIGN ELEMENTS	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	GROUND	ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED						
I V A	A1 C5	A1 C2 C5 C13	A1 C1 C5 C13	A1 D5 E3	A2 A5 A6 D5 D6 F11	A1 D5 D6 F11	A2 A5 A6 D3 D6 D7 D8,F12*
E V A	A1 B1 C5 C13	A1 B1 C2 C5 C13	A1 B1 B14 C1 C5 C13				

EXAMPLE - Adjust/Regulate Thermal Fluid Flow Rate to External Radiator

MANUAL - Hand Activated Valve
SUPPORTED - Tool Assisted Valve
AUGMENTED - Power Tool Assisted Valve
TELEOPERATED - Remote Satellite Servicer for Manual Valve
SUPERVISED GROUND - Mechanized Valve On Space Platform
SUPERVISED ON-ORBIT - Mechanized Valve On Space Platform
INDEPENDENT - Self Monitoring and Adjusting Automatic Valve

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* Considered as one item of support equipment
D8 - Computer Hardware
F12 - Associated Software

SUPPORT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 3	CATEGORIES OF MAN-MACHINE INTERACTIONS						
					SUPERVISED		
ALLOCATE/ASSIGN DISTRIBUTE	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	GROUND	ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED						
I V A	A1 C2	A1 B7 C2 C6 C13	A1 C2 C6 C13 D7	A1 D5 E3	A2 A5 A6 D5 D6 F11	A1 D5 D6 F11	A2 A5 A6 D3 D6 D7 D8,F12*
E V A							

EXAMPLE - Power Disruption from Failed Solar Array, Required to Reassign Power Pouting and Reallocate and Redistribute Power

MANUAL - Switch by Hand and Circuit Breaker Control
SUPPORTED - Troubleshooting and Switching and Circuit Breaker Control
AUGMENTED - Troubleshooting with Aid of Data File and Displays
TELEOPERATED - Remote Satellite Serviced By Telepresence Manipulator System
SUPERVISED GROUND - Ground Commanded Switching on Remote Platform
SUPERVISED ON-ORBIT - On-Orbit Commanded Switching of Remote Platform
INDEPENDENT - Self-healing Systems

* Considered as one item of support equipment
D8 - Computer Hardware
F12 - Associated Software

SUPPORT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 4	CATEGORIES OF MAN-MACHINE INTERACTIONS						
					SUPERVISED		
APPLY/REMOVE BIOMEDICAL SENSOR	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	GROUND	ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED						
I V A	A1 C14	A1 C14 C13	A1 C11 C13 C14				
E V A							

EXAMPLE - Attach Pickup Electrodes to Subject

MANUAL - Cleanse Tissue Area, Apply Sensors
SUPPORTED - Cleanse Tissue Area, Apply Sensors
AUGMENTED - Microscopic Installation of Sensor
TELEOPERATED - Not Applicable
SUPERVISED GROUND - Not Applicable
SUPERVISED ON-ORBIT - Not Applicable
INDEPENDENT - Not Applicable

SUPPOPT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 5	CATEGORIES OF MAN-MACHINE INTEPACTIONS						
					SUPERVISED		
COMMUNICATE INFORMATION	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	GROUND	ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED						
I V A	A1	A1 C13 D4	A1 D4 D5	A1 B3 D5	A2 A5 A6 D5 D6 F11	A1 D5 D6 F11	A2 A5 A6 D3 D6 D7 D8,F12*
E V A	A1 B1 C13	A1 B1 C13 D4					

EXAMPLE - Transmit Data

MANUAL - Verbal Voice Communication
SUPPORTED - Voice Activated Communication System
AUGMENTED - Intercom Voice Communication
TELEOPERATED - Command/Control of Remote Manipulator System
SUPERVISED GROUND - Commanded Data Link Transmission
SUPERVISED ON-ORBIT - Commanded Data Link Transmission
INDEPENDENT - Spacecraft Autonomous Data Link Transmission

*Considered as one item of support equipment
D8 - Computer Hardware
F12 - Associated Software

SUPPORT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 6	CATEGORIES OF MAN-MACHINE INTERACTIONS						
COMPENSATORY TRACKING	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	SUPERVISED GROUND	SUPERVISED ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED						
I V A					A2 A5 A6 D3 D5 D6 F11	A1 D3 D5 D6 F11	A2 A5 A6 D3 D6 D7 D8,F12*
E V A							

EXAMPLE: Antenna Lock-on and Track TDRSS

MANUAL - Not Applicable
SUPPORTED - Not Applicable
AUGMENTED - Not Applicable
TELEOPERATED - Not Applicable
SUPERVISED GROUND - Command Auto Track System
SUPERVISED ON-ORBIT - Command Auto Track System
INDEPENDENT - Pre-programmed Auto Track System

*Considered as one item of support equipment
D8 - Computer Hardware
F12 - Associated Software

SUPPORT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 7	CATEGORIES OF MAN-MACHINE INTERACTIONS						
COMPUTE DATA	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	SUPERVISED GROUND	SUPERVISED ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED						
I V A	A1	A1 C8 C13	A1 C13 D10		A2 A6 A7 D5 F10	A1 D5 D10 F10	A2 A5 A6 D7 D8,F12*
E V A							

EXAMPLE - Determine Spacecraft Position From Sensor Data

MANUAL - Manual Computation
SUPPORTED - Use of Hand Computation Equipment
AUGMENTED - Computer Aided Computation
TELEOPERATED - Not Applicable
SUPERVISED GROUND - Command Software Program Computation
SUPERVISED ON-ORBIT - Command Software Program Computation
INDEPENDENT - Self-initiated Software Program For Computation

* Considered as one item of support equipment
D8 - Computer Hardware
F12 - Associated Software

SUPPORT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 8	CATEGORIES OF MAN-MACHINE INTERACTIONS						
					SUPERVISED		
CONFIRM/VERIFY PROCEDURE/SCHEDULE OPERATIONS	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	GROUND	ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED						
I V A	A1	A1 C13	A1 C13 D7	A1 D2 E3	A2 A5 A6 C9 D2 D6 F11	A1 C9 D2 D6 F11	A2 A5 A6 D3 D7 D8,F12*
E V A	A1 B1 C13						

EXAMPLE - Confirm/Verify Solar Array Deployment

MANUAL - Visual Look
SUPPORTED - Visual Look Aided By Status Indicator
AUGMENTED - Display Of Go/No-Go With Audio No-Go Signal
TELEOPERATED - Verify With Remote T.V. (T.M.S.)
SUPERVISED GROUND - Command Verification with Remote T.V.
SUPERVISED ON-ORBIT - Command Verification with Remote T.V.
INDEPENDENT - Auto Status With Self Fix For No-Go Indication

* Considered as one item of support equipment
D8 - Computer Hardware
F12 - Associated Software

SUPPORT EQUIPMENT PEQUIPEMENTS

ACTIVITY NUMBER: 9	CATEGORIES OF MAN-MACHINE INTERACTIONS						
					SUPERVISED		
CONNECT/DISCONNECT ELECTRICAL INTERFACE	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	GROUND	ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED						
I V A	A1 C2	A1 C2 C13	A1 C1 C13	A1 D5 E3	A2 A5 A6 D5 D6 F11	A1 D5 D6 F11	A2 A5 A6 D3 D6 D7 D3,F12*
E V A	A1 B1 C2 C13	A1 B1 C2 C13	A1 B1 C1 C13				

EXAMPLE - Electrical Interface Connector Plate

MANUAL - Manual Ratchet
SUPPORTED - Manual Ratchet with Restraints
AUGMENTED - Power Tool Application
TELEOPERATED - T.M.S. Activated Ratcheting Operation
SUPERVISED GROUND - Mechanized Drive Operation
SUPERVISED ON-ORBIT - Mechanized Drive Operation
INDEPENDENT - Mechanized Drive Operation

* Considered as one item of support equipment
D8 - Computer Hardware
F12 - Associated Software

SUPPORT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 10	CATEGORIES OF MAN-MACHINE INTERACTIONS						
					SUPERVISED		
CONNECT/DISCONNECT FLUID INTERFACE	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	GROUND	ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED						
I V A	A1 C2	A1 C2 C13	A1 C1 C13	A1 D5 E3	A2 A5 A6 D5 D6 F11	A1 D5 D6 F11	A2 A5 A6 D3 D6 D7 D8,F12*
E V A	A1 B1 C2 C13	A1 B1 C2 C13	A1 B1 C1 C13				

EXAMPLE - Fluid Interface Connector Plate

MANUAL - Manual Ratchet
SUPPORTED - Manual Ratchet with Restraints
AUGMENTED - Power Tool Application
TELEOPERATED - T.M.S. Activated Ratcheting Operation
SUPERVISED GROUND - Mechanized Drive Operation
SUPERVISED ON-ORBIT - Mechanized Drive Operation
INDEPENDENT - Mechanized Drive Operation

*Considered as one item of support equipment
D8 - Computer Hardware
F12 - Associated Software

SUPPOPT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 11	CATEGORIES OF MAN-MACHINE INTERACTIONS						
					SUPEPVISED		
CORRELATE DATA	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	GROUND	ON ORBIT	INDEPENDENT
	HUMAN SUPPOPT EQUIPMENT REQUIPED						
I V A	A1	A1 C13	A1 C13 D5 F10		A2 A3 A6 D5 F9	A1 D5 F9	A2 A5 A6 D7 D8,F12*
E V A							

EXAMPLE - Perform An Evaluation To Correlate Data Obtained From An Orbital Experiment

MANUAL - Visual Or Long Hand Derived Evaluation
SUPPORTED - Visual Or Long Hand Derived Evaluation With Restraints
AUGMENTED - Evaluation Performed With Aid Of Computer
TELEOPERATED - Not Applicable
SUPERVISED GROUND - Software Performed Evaluation
SUPERVISED ON-ORBIT - Software Performed Evaluation
INDEPENDENT - Software Performed Evaluation

* Considered as one item of support equipment
D8 - Computer Hardware
F12 - Associated Software

SUPPORT EQUIPMENT PEQUIPEMENTS

ACTIVITY NUMBER: 12	CATEGORIES OF MAN-MACHINE INTERACTIONS						
					SUPERVISED		
DEACTIVATE/ TERMINATE SYSTEM OPERATION	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	GROUND	ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED						
I V A	A1 C8	A1 C8 C13	A1 C9 C13	A1 C10 D5 D6	A2 A5 A6 D5 D6 F11	A1 D5 D6 F11	A2 A3 A4 A5 A6 D3 D6 D7 D8,F12*
E V A	A1 B1 C8 C13	A1 B1 C8 C13	A1 B1 C9 C13				

EXAMPLE - Deactivate Camera/Imaging Equipment

MANUAL - Deactivate 35mm Camera
SUPPORTED - Deactivate 35mm Camera
AUGMENTED - Deactivate Video Camera From Console With Rotary Selector Switch
TELEOPEPATED - Deactivate Remote Video Camera
SUPERVISED GROUND - Deactivate Remote Video Camera
SUPERVISED ON-OPBIT - Deactivate Pemote Video Camera
INDEPENDENT - Deactivate Imaging System

* Considered as one item of support equipment
D8 - Computer Hardware
F12 - Associated Software

SUPPORT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 13	CATEGORIES OF MAN-MACHINE INTERACTIONS						
					SUPERVISED		
DECODE/ENCODE DATA	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	GROUND	ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED						
I V A	A1	A1	A1 C13 D5		A2 A5 A6 D5 D9 F10	A1 D5 D9 F10	A2 A5 A6 D3 D7 D8 D9 F12
E V A	A1 B1 C13	A1 B1 C13					

EXAMPLE - Transform Data From One Format to Another

MANUAL - Decode Sample Meter Reading
SUPPORTED - Decode Auditory Warning Signal
AUGMENTED - Decode Complex Data Format
TELEOPERATED - Not Applicable
SUPERVISED GROUND - Decode Command From Ground Control
SUPERVISED ON-ORBIT - Decode Command From On-Orbit Control
INDEPENDENT - Auto Command From Selfcontrolled and Monitoring System

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*Considered as one item of support equipment
D8 - Computer Hardware
F12 - Associated Software

SUPPORT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 14	CATEGORIES OF MAN-MACHINE INTERACTIONS						
					SUPERVISED		
DEFINE PROCEDURES/ SCHEDULES/OPERATIONS	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	GROUND	ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED						
I V A	A1	A1 C13	A1 C13 D7		A2 A5 A6 D5 D7 F11	A1 D5 D7 F11	A2 A5 A6 D3 D7 D8,F12*
E V A							

EXAMPLE - Define Procedures For Troubleshoting A Faulty Component

MANUAL - Crewman Determination Of Procedures
SUPPORTED - Crewman Restrained-Determination Of Procedures
AUGMENTED - Computer Aided Procedure Determination
TELEOPERATED - Not Applicable
SUPERVISED GROUND - Commanded Software Generation Of Procedures
SUPERVISED ON-ORBIT - Commanded Software Generation Of Procedures
INDEPENDENT - Self-Initiated Software Generation Of Procedures

*Considered as one item of support equipment
D8 - Computer Hardware
F12 - Associated Software

SUPPORT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 15	CATEGORIES OF MAN-MACHINE INTERACTIONS						
					SUPERVISED		
DEPLOY/RETRACT APPENDAGE	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	GROUND	ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED						
I V A				A1 D5 E3	A2 A5 A6 D5 D6 F11	A1 D5 D6 F11	A2 A5 A6 D3 D6 D7 D8,F12*
E V A	A1 B1 C2 C13	A1 B1 C2 C13	A1 B1 C1 C13				

EXAMPLE - Deploy Solar Array

MANUAL - Manually Hand Cranked
SUPPORTED - Manually Hand Cranked Aided With Restraint
AUGMENTED - Power Tool Assisted
TELEOPERATED - Not Applicable
SUPERVISED GROUND - Mechanized Drive
SUPERVISED ON-ORBIT - Mechanized Drive
INDEPENDENT - Mechanized Drive

*Considered as one item of support equipment
D8 - Computer Hardware
F12 - Associated Software

SUPPORT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 16	CATEGORIES OF MAN-MACHINE INTERACTIONS						
					SUPERVISED		
DETECT CHANGE IN STATE OR CONDITION	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	GROUND	ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED						
I V A	A1	A1 C13	A1 D5 C13	A1 D5 D6 E1	A2 A5 A6 D5 D23 F11	A1 D5 D23 F11	A2 A5 A6 D7 D8 D8,F12* D23
E V A	A1 B1 C13	A1 B1 C13	A1 B1 C6 C13				

EXAMPLE - Detect Change In Condition Of Solar Array Elements

MANUAL - Visual Determination
SUPPORTED - Visual Determination Aided With Restraint
AUGMENTED - Electrical Test Set Checkout
TELEOPERATED - OMV TV Inspection
SUPERVISED GROUND - Commanded Monitoring Of Solar Array Power Generation
SUPERVISED ON-ORBIT - Commanded Monitoring Of Solar Array Power Generation
INDEPENDENT - Automatic Monitoring And Detection Of Solar Array Power Output

* Considered as one item of support equipment
D8 - Computer Hardware
F12 - Associated Software

SUPPORT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 17	CATEGORIES OF MAN-MACHINE INTEPACTIONS						
DISPLAY DATA	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	SUPERVISED GROUND	SUPERVISED ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIPED						
I V A	A1	A1 D5 C13	A1 C9 C13 D5	A1 D5 E1	A2 A5 A6 D5 F10	A1 D5 F10	A2 A3 A5 A6 D7 D8,F12*
E V A							

EXAMPLE - Display Daily Mission Activity Log

MANUAL - Obtain Pre-printed Mission Activity Log
SUPPOPTED - Obtain Pre-printed Mission Activity Log
AUGMENTED - Obtain Logs Via Simple Computer Display
TELEOPEPATED - Obtain Logs Via Data Link From A Pemote Station
SUPERVISED GROUND - Computer Displayed Activity Logs
SUPERVISED ON-ORBIT - Computer Displayed Activity Logs
INDEPENDENT - Computer Displayed Activity Logs

* Considered as one item of support equipment
D8 - Computer Hardware
F12 - Associated Software

SUPPORT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 18	CATEGORIES OF MAN-MACHINE INTERACTIONS						
GATHER/REPLACE TOOLS/EQUIPMENT	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	SUPERVISED GROUND	SUPERVISED ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED						
I V A	A1 C2	A1 C2 C13	A1 C1 C13	D5 A1 E3 F10			
E V A	B1 A1 C2 C13	B1 A1 C2 C13	B1 A1 C1 C13				

EXAMPLE - Gather The Required Tools To Perform A Module Exchange

MANUAL - Gather Simple Tools
SUPPORTED - Gather More Complex Tools Requiring Restraints
AUGMENTED - Gather Power And Standard Tools
TELEOPERATED - Gather Tools From Remote Area With TMS
SUPERVISED GROUND - Not Applicable
SUPERVISED ON-ORBIT - Not Applicable
INDEPENDENT - Not Applicable

SUPPORT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 19	CATEGORIES OF MAN-MACHINE INTEPACTIONS						
					SUPERVISED		
HANDLE/INSPECT/ EXAMINE LIVING ORGANISMS	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	GROUND	ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED						
I V A	A1 C14	A1 C13 C14	A1 C9 C13	A1 C9 D2 D6		A1 D5 D6 D23 F10	
E V A							

EXAMPLE - Examine To Determine The Health Status Of A Rat

MANUAL - Visual Examination
SUPPORTED - Visual Examination With Use Of Restraints
AUGMENTED - Use Of Electronic Monitoring Equipment
TELEOPERATED - Examine/Inspect by Use of CCTV System
SUPERVISED GROUND - Not Applicable
SUPERVISED ON-ORBIT - Examine Printout From Instrumented Rat
INDEPENDENT - Not Applicable

SUPPORT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 20	CATEGORIES OF MAN-MACHINE INTERACTIONS						
					SUPERVISED		
IMPLEMENT PROCEDURES/SCHEDULES	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	GROUND	ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED						
I V A	A1	A1 C13	A1 C13 D7	A1 D5 E3	A2 A5 A6 D5 D6 F11	A1 D5 D6 F11	A2 A5 A6 D3 D6 D7 D8,F12*
E V A	A1 B1 C13	A1 B1 C13					

EXAMPLE - Implement Procedures To Troubleshoot A Faulty Component

MANUAL - Vocal Command To Implement
SUPPORTED - Manually Implement Procedures From Restraints
AUGMENTED - Computer Aided Implementation Of Maintenance Procedures
TELEOPERATED - Implement Procedures Through Use Of TMS
SUPERVISED GROUND - Command Software Implementation Of Procedures
SUPERVISED ON-ORBIT - Command Software Implementation Of Procedures
INDEPENDENT - Self-Initiated Software Implementation Of Procedures

* Considered as one item of support equipment
D8 - Computer Hardware
F12 - Associated Software

SUPPORT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 21	CATEGORIES OF MAN-MACHINE INTERACTIONS						
					SUPERVISED		
INFORMATION PROCESSING	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	GROUND	ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED						
I V A	A1 C8	A1 C9 C13	A1 C10 F8		A2 A5 A6 D5 F8 F10	A1 D5 F8 F10	A2 A5 A6 D7 D8,F12* F8
E V A	A1 B1 C8 C13						

EXAMPLE - Extract A Specific Maintenance Procedure

MANUAL - Visual Flip-Through For Specific Checklist
SUPPORTED - Auto Flip-Through For Specific Checklist
AUGMENTED - Call Up Procedure From Computer Data Bank
TELEOPERATED - Not Applicable
SUPERVISED GROUND - Command Maintenance Procedure For An Identified Failed Item
SUPERVISED ON-ORBIT - Command Maintenance Procedure For An Identified Failed Item
INDEPENDENT - Auto Command For Detection Procedure For A Failed Item

* Considered as one item of support equipment
D8 - Computer Hardware
F12 - Associated Software

SUPPORT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 22	CATEGORIES OF MAN-MACHINE INTEPACTIONS						
					SUPERVISED		
INSPECT/OBSERVE	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	GROUND	ON ORBIT	INDEPENDENT
	HUMAN SUPPOPT EQUIPMENT PEQUIRED						
I V A	A1	A1 C13	A1 C10 C13	A1 B3 C10 D2	A2 A3 A5 A6 D5 D6 F11	A1 A5 D5 D6 F11	A2 A3 A5 A6 D3 D6 D7 D8,F12*
E V A	A1 B1 C13	A1 B1 C13	A1 B1 C10 C13				

EXAMPLE - Make Observation Of Solar Activity

MANUAL - Visual Observation
SUPPORTED - Visual Observation With Restraints
AUGMENTED - Visual Observation Aided By Solar Viewer
TELEOPERATED - External Video Camera Operation On PMS
SUPERVISED GROUND - Commanded IR Viewing System
SUPERVISED ON-ORBIT - Commanded IR Viewing System
INDEPENDENT - Commanded IR Viewing By Preprogrammed Command Signal

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*Considered as one item of support equipment
D8 - Computer Hardware
F12 - Associated Software

SUPPORT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 23	CATEGORIES OF MAN-MACHINE INTERACTIONS						
MEASURE (SCALE) PHYSICAL DIMENSIONS	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	SUPERVISED GROUND	SUPERVISED ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED						
I V A	A1 C8	A1 C8 C13	A1 C13 D23	A1 D5 D23 E3	A2 A5 A6 D5 D6	A1 D5 D6 D23	A2 A5 A6 D6 D7 D8,F12* D23
E V A	A1 B1 C8 C13	A1 B1 C8 C13	A1 B1 C13 D23				

EXAMPLE - Determine Distance Between Spacecraft And Desired Target

MANUAL - Visual Determination
SUPPORTED - Visual Determination Aided By COAS (Crew Optical Alignment Sight)
AUGMENTED - Determination By Radar System
TELEOPERATED - Determination By Remote Sensor/Visual System
SUPERVISED GROUND - Commanded Telemetry Data
SUPERVISED ON-ORBIT - Commanded Telemetry Data
INDEPENDENT - Preprogrammed Signal For Commanded Telemetry Data

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* Considered as one item of support equipment
D8 - Computer Hardware
D12 - Associated Software

SUPPORT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 24	CATEGORIES OF MAN-MACHINE INTERACTIONS						
					SUPERVISED		
PLOT DATA	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	GROUND	ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED						
I V A	A1	A1 C9 C13	A1 C10 C13 D5		A2 A3 A4 A5 A6 D5 F10	A1 D5 F10	A2 A3 A4 A5 A6 D7 D8,F12*
E V A							

EXAMPLE - Plot Experiment Derived Data For Evaluation Purposes

MANUAL - Manual Plot
SUPPORTED - Manual Plot With Hand Calculator And Restraint Aid(s)
AUGMENTED - Use Computer To Plot Data
TELEOPERATED - Not Applicable
SUPERVISED GROUND - Command Computer To Plot Routine
SUPERVISED ON-ORBIT - Command Computer To Plot Routine
INDEPENDENT - Preprogrammed Signal To Command Computer To Plot Routine

* Considered as one item of support equipment
D8 - Computer Hardware
F12 - Associated Software

SUPPORT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 25	CATEGORIES OF MAN-MACHINE INTERACTIONS						
					SUPERVISED		
POSITION MODULE	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	GROUND	ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED						
I V A	A1	A1 C13	A1 C8 C13	A1 D5 E3	A2 A5 A6 D5 D6 F11	A1 D5 D6 F11	
E V A	A1 B1 C13	A1 B1 C13	A1 B1 C8 C13				

EXAMPLE - Position Sample Material Container In Its Installation Position In Material Processing Experiment

MANUAL - Manually Installed
SUPPORTED - Manually Installed With Aid Of Restraints
AUGMENTED - Installation Aided By Deployable Positioning Device
TELEOPERATED - Installed Remotely By TMS
SUPERVISED GROUND - Ground Commanded Carousel Positioning Device
SUPERVISED ON-ORBIT - Orbital Command of Carousel Positioning Device
INDEPENDENT - Not Applicable

SUPPORT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 26	CATEGORIES OF MAN-MACHINE INTERACTIONS						
PRECISION MANIPULATION OF OBJECTS	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	SUPERVISED GROUND	SUPERVISED ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED						
I V A	A1	A1 C13 C8	A1 C13 C10				
E V A	B1 A1 C13	B1 A1 C13 C8	B1 A1 C13 C10				

EXAMPLE - Precise Alignment Of Optical Viewing Device

MANUAL - Manual Hand Adjustment
SUPPORTED - Manual Adjustment Aided By Mechanical Screw Adjuster
AUGMENTED - Fine Adjustment Aided By Electro-optical Alignment Device
TELEOPERATED - Not Applicable
SUPERVISED GROUND - Not Applicable
SUPERVISED ON-ORBIT - Not Applicable
INDEPENDENT - Not Applicable

SUPPORT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 27	CATEGORIES OF MAN-MACHINE INTERACTIONS						
					SUPERVISED		
PROBLEM SOLVING/ DECISION MAKING/ DATA ANALYSIS	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	GROUND	ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED						
I V A	A1 C2	A1 C2 C13	A1 C2 C6 C13	A1 B3 D5	A2 A5 A6 D5 D23 F10	A1 D5 D23 F10	A2 A5 A6 D7 D8,F12* D23
E V A	A1 B1 C2 C13	A1 B1 B2 C13	A1 B1 C2 C6 C13				

EXAMPLE - Troubleshoot/Fault Isolate Malfunction In Failed Unit

MANUAL - Manually Troubleshoot
SUPPORTED - Manually Troubleshoot With Aid Of Restraints
AUGMENTED - Use Test Set For Fault Isolation
TELEOPERATED - Troubleshoot Remote Item Utilizing RMS
SUPERVISED GROUND - Command Fault Isolation Program
SUPERVISED ON-ORBIT - Command Fault Isolation Program
INDEPENDENT - Preprogrammed Signal To Command Fault Isolation Program

* Considered as one item of support equipment
D8 - Computer Hardware
F12 - Associated Software

SUPPORT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 28	CATEGORIES OF MAN-MACHINE INTERACTIONS						
PURSUIT TRACKING	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	SUPERVISED GROUND	SUPERVISED ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED						
I V A	A1	A1 C13 C8	A1 C13 C10	D2 A1 B3			
E V A							

EXAMPLE - Docking And Latching Of RMS After Usage

MANUAL - Visual Tracking
SUPPORTED - Visual Tracking With Aid Of Restraints
AUGMENTED - Visual Tracking With Aid Of Zoom TV On RMS
TELEOPERATED - Bulkhead Mounted T.V. Cameras Expand Visual Coverage
SUPERVISED GROUND - Not Applicable
SUPERVISED ON-ORBIT - Not Applicable
INDEPENDENT - Not Applicable

SUPPORT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 29	CATEGORIES OF MAN-MACHINE INTERACTIONS						
					SUPERVISED		
RELEASE/SECURE MECHANICAL INTERFACE	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	GROUND	ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED						
I V A	A1 C2	A1 C2 C13	A1 C1 C13	A1 D5 E3	A2 A5 A6 D5 D6 F11	A1 D5 D6 F11	A2 A5 A6 D3 D6 D7 D8,F12*
E V A	A1 B1 C2 C13	A1 B1 C2 C13	A1 B1 C1 C13				

EXAMPLE - Release Latching Mechanism

MANUAL - Manual Activation
SUPPORTED - Manual Activation With Restraints
AUGMENTED - Activation With Use Of Power Tool
TELEOPERATED - TMS Operation To Activate Mechanism
SUPERVISED GROUND - Command Signal To Activate Mechanism
SUPERVISED ON-ORBIT - Command Signal To Activate Mechanism
INDEPENDENT - Preprogrammed To Command A Signal To Activate Mechanism

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* Considered as one item of support equipment
D8 - Computer Hardware
F12 - Associated Software

SUPPORT EQUIPMENT REQUIPEMENTS

ACTIVITY NUMBER: 30	CATEGORIES OF MAN-MACHINE INTERACTIONS						
REMOVE MODULE	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	SUPEPVISED GROUND	SUPEPVISED ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIPED						
I V A	A1	A1 C13	A1 C8 C13	A1 B3 D5	A2 A5 A6 D5 D6 F11	A1 D5 D6 F11	
E V A	A1 B1 C13	A1 B1 C13	A1 B1 C8 C13				

EXAMPLE - Remove A Sample Material Container From Its Mounting Location, Mechanical Interface Has Been Released

MANUAL - Manual Hand Action
SUPPORTED - Manual Hand Action Aided By Restraint
AUGMENTED - Pemoval Of Module With Special Tool
TELEOPERATED - RMS Utilized To Grasp And Remove Module
SUPEPVISED GROUND - Ground Commanded Carousel Device
SUPERVISED ON-ORBIT - Orbital Command of Carousel Device
INDEPENDENT - Not Applicable

SUPPORT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 31	CATEGORIES OF MAN-MACHINE INTERACTIONS						
					SUPERVISED		
REMOVE/REPLACE COVERING	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	GROUND	ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED						
I V A	A1 C2	A1 C2 C13	A1 C1 C13	A1 D5 E3	A2 A5 A6 D5 D6 F11	A1 D5 D6 F11	A2 A5 A6 D6 D7 D8,F12*
E V A	A1 B1 C2 C13	A1 B1 C2 C13	A1 B1 C1 C13				

EXAMPLE - Remove Cover For Optical Telescope System

MANUAL - Manual Removal
SUPPORTED - Manual Removal Aid By Restraints
AUGMENTED - Removal Aided By Power Tool
TELEOPERATED - Aided By TMS Removal Operation
SUPERVISED GROUND - Command Opening Of Optical Covering
SUPERVISED ON-ORBIT - Command Opening Of Optical Covering
INDEPENDENT - Preprogrammed Signal To Command Opening Of Optical Covering

*Considered as one item of support equipment
D8 - Computer Hardware
F12 - Associated Software

SUPPORT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 32	CATEGORIES OF MAN-MACHINE INTERACTIONS						
					SUPERVISED		
REPLACE/CLEAN SURFACE COATINGS	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	GROUND	ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED						
I V A	A1 C2	A1 C2 C13	C7 A1 C13	D5 A1 E3 C7			
E V A	B1 A1 C13 C2	B2 A1 B1 C13 C2	B1 C12 A1 C13 C7				

EXAMPLE - Clean Radiator Surface Coating

MANUAL	- Manually Clean With Simple Tools
SUPPORTED	- Manually Clean Large Areas, Use MMU For EVA
AUGMENTED	- Use Power Cleaning Apparatus On MFR (Manipulator Foot Restraint)
TELEOPERATED	- Use TMS With Power Cleaning Apparatus
SUPERVISED GROUND	- Not Applicable
SUPERVISED ON-ORBIT	- Not Applicable
INDEPENDENT	- Not Applicable

SUPPORT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 33	CATEGORIES OF MAN-MACHINE INTERACTIONS						
					SUPERVISED		
REPLENISH MATERIALS	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	GROUND	ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED						
I V A	A1 C9	A1 C9 C13	A1 C4 C13	A1 C4 D5 E3	A2 A5 A6 D5 D6 D23 F11	A1 D5 D6 D23 F11	A2 A5 A6 D3 D6 D7 D8,F12* D23
E V A	A1 B1 C9 C13	A1 B1 C9 C13	A1 B1 C4 C13				

EXAMPLE - Recharge Low Fluid Level In Thermal Control System

MANUAL - Manually Hand Pump Fluid Into System
SUPPORTED - Manually Hand Pump Fluids Into System Aided By Restraints
AUGMENTED - Utilize Fluid Recharge Kit
TELEOPERATED - TMS Operation With Fluid Recharge Kit
SUPERVISED GROUND - Command Fluid Transfer From Reserve To System
SUPERVISED ON-ORBIT - Command Fluid Transfer From Reserve To System
INDEPENDENT - Auto-Command To Transfer Fluid From Reserve To System

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* Considered as one item of support equipment
D8 - Computer Hardware
F12 - Associated Software

SUPPOPT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 34	CATEGORIES OF MAN-MACHINE INTERACTIONS						
STORE/RECORD ELEMENT	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	SUPERVISED GROUND	SUPERVISED ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIPED						
I V A	A1	A1 C13	A1 D5 C13	A1 D5 E1	A2 A5 A6 D5 F11	A1 D5 F11	A2 A5 A6 D7 D8,F12*
E V A	A1 B1 C13	A1 B1 C13	A1 B1 C13				

EXAMPLE - Record Observational Data

MANUAL - Manual Record
SUPPORTED - Manual Record Aided By Restraints
AUGMENTED - Use Of Computer To Record Data
TELEOPERATED - OMV Video Recording Of Data
SUPERVISED GROUND - Command Recording Of Data
SUPERVISED ON-OPBIT - Command Pecording Of Data
INDEPENDENT - Auto-Command Signal To Record Data

*Considered as one item of support equipment
D8 - Computer Hardware
F12 - Associated Software

SUPPORT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 35	CATEGORIES OF MAN-MACHINE INTERACTIONS						
					SUPERVISED		
SURGICAL MANIPULATIONS	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	GROUND	ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED						
I V A	A1 C14	A1 C14 C8	A1 C14 C9				
E V A							

EXAMPLE - Obtain Tissue Sample From Subject

MANUAL - Manual Use Of Simple Surgical Instrument
SUPPORTED - Special Surgical Tool/Instrument
AUGMENTED - Use Microscope To Aid Removal Of Tissue
TELEOPERATED - Not Applicable
SUPERVISED GROUND - Not Applicable
SUPERVISED ON-ORBIT - Not Applicable
INDEPENDENT - Not Applicable

SUPPORT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 36	CATEGORIES OF MAN-MACHINE INTERACTIONS						
TRANSPORT LOADED	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	SUPERVISED GROUND	SUPERVISED ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT REQUIRED						
I V A	A1	A1 C13		A1 B3 D5			
E V A	A1 B1 C13	A1 B1 C13	A1 B1 B2 C13				

EXAMPLE - Transport Replaceable Unit To Its Installation Location

MANUAL - Manual Translation
SUPPORTED - Manual Translation With Tethers And Handholds
AUGMENTED - Translation With MMU
TELEOPERATED - Translation With RMS
SUPERVISED GROUND - Not Applicable
SUPERVISED ON-ORBIT - Not Applicable
INDEPENDENT - Not Applicable

NOTE: Transport Loaded operations beyond the normal working environment (e g., to geosynchronous orbit) could require many hours. In the foreseeable future such activities would be performed only in the Supervised or Independent modes. Ther fore in the THURIS study costing analyses, transport operations beyond the normal working environment were not considered.

SUPPOPT EQUIPMENT REQUIREMENTS

ACTIVITY NUMBER: 37	CATEGORIES OF MAN-MACHINE INTERACTIONS						
					SUPEPVISED		
TRANSPORT UNLOADED	MANUAL	SUPPORTED	AUGMENTED	TELEOPERATED	GROUND	ON ORBIT	INDEPENDENT
	HUMAN SUPPORT EQUIPMENT PEQUIRED						
I V A	A1	A1 C13		A1 B3 D5			
E V A	A1 B1 C13	A1 B1 C13	A1 B1 B2 C13				

EXAMPLE - Translate From Work Location To Obtain Replacement Unit

MANUAL - Manual Translation
SUPPORTED - Manual Translation With Tethers And Handholds
AUGMENTED - Translation With MMU
TELEOPERATED - Translation With RMS
SUPERVISED GROUND - Not Applicable
SUPERVISED ON-ORBIT - Not Applicable
INDEPENDENT - Not Applicable

NOTE: Transport Unloaded operations beyond the normal working environment (e.g., to geosynchronous orbit) could require many hours. In the foreseeable future, such activities would be performed only in the Supervised or Independent modes. Therefore in the THURIS study costing analyses, transport operations beyond the normal working environment were not considered.

APPENDIX F

CUMULATIVE COSTS AS A FUNCTION OF NUMBER OF TIMES ACTIVITY IS PERFORMED FOR SEVEN MAN-MACHINE MODES

INDEX

LEGEND

Manual

Supported

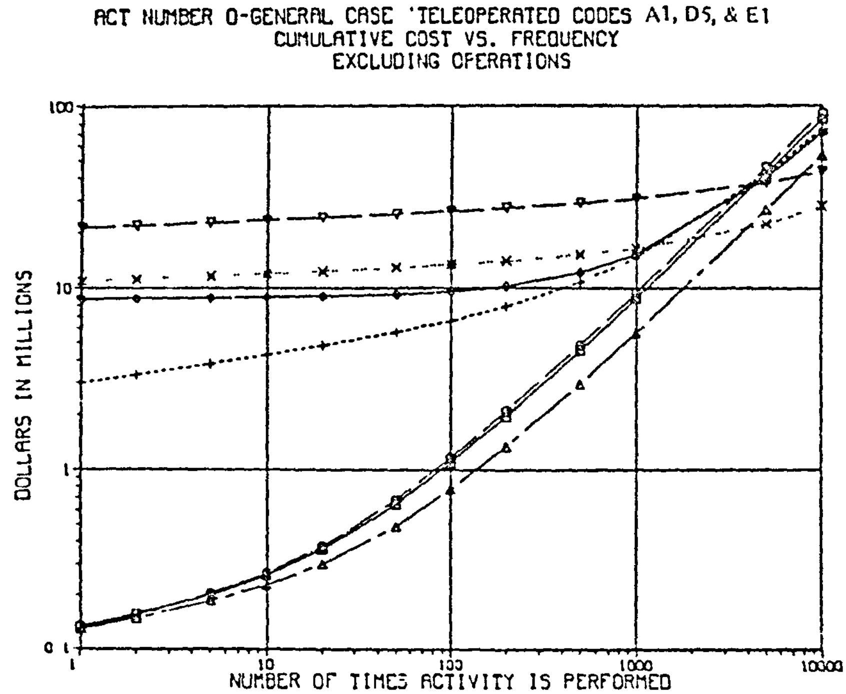
Augmented

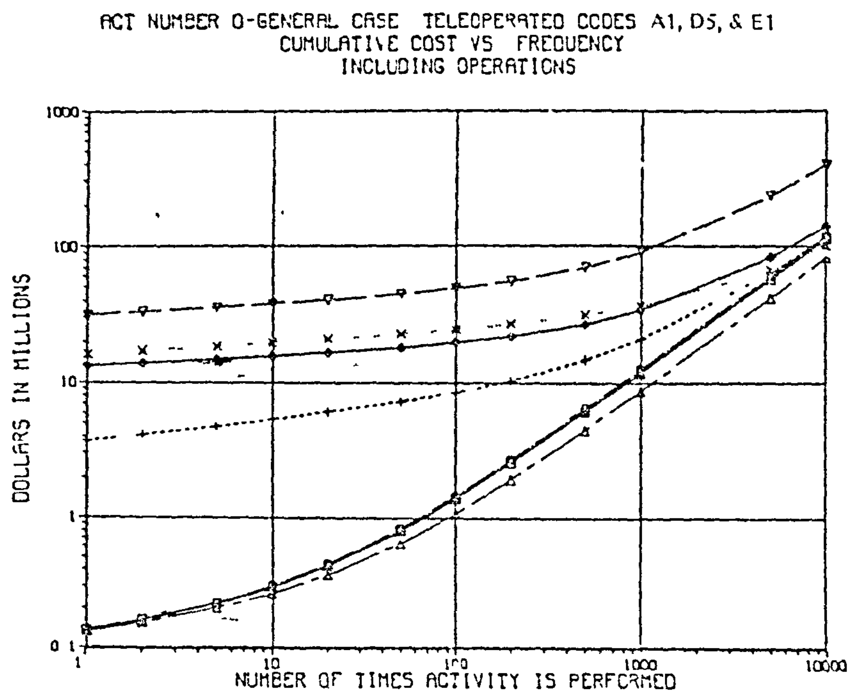
Teleoperated

Supervised - Ground

Supervised - On Orbit

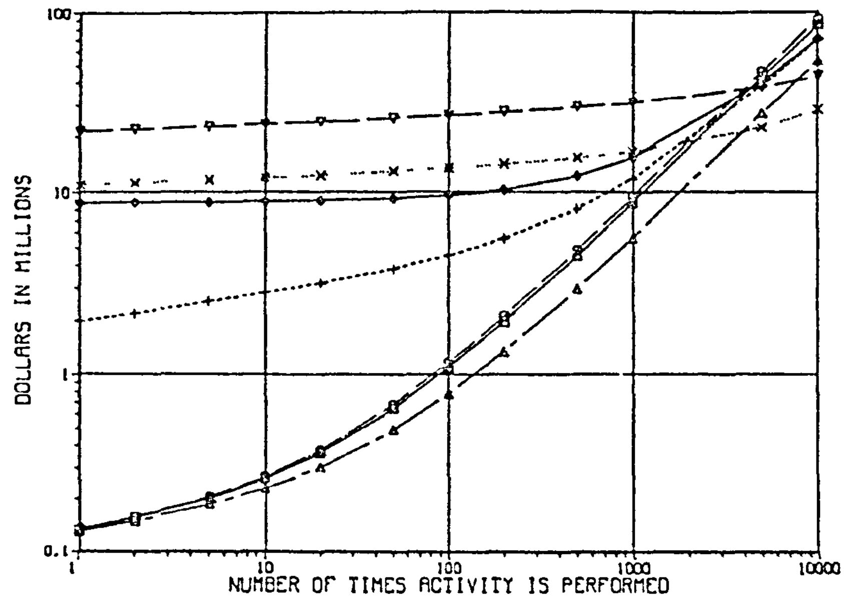
Independent



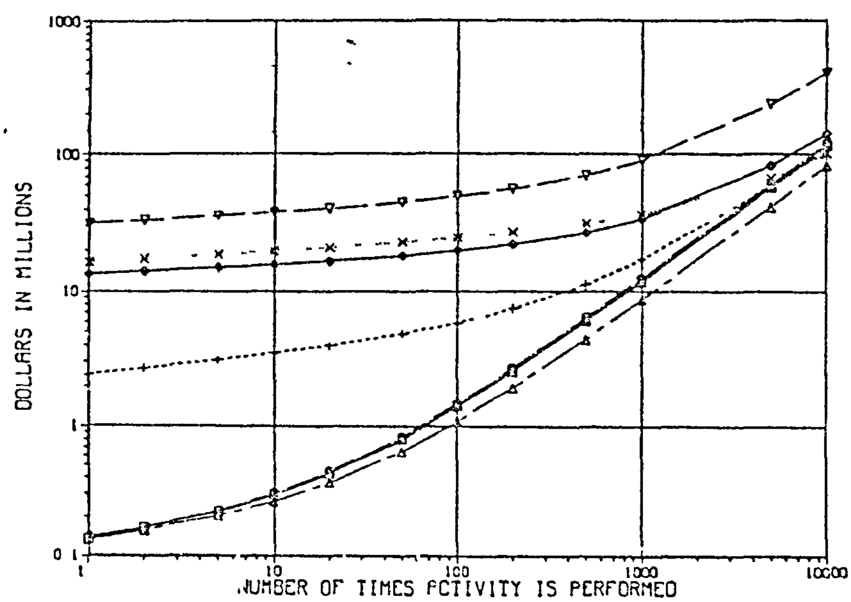


MCDONNELL DOUGLAS

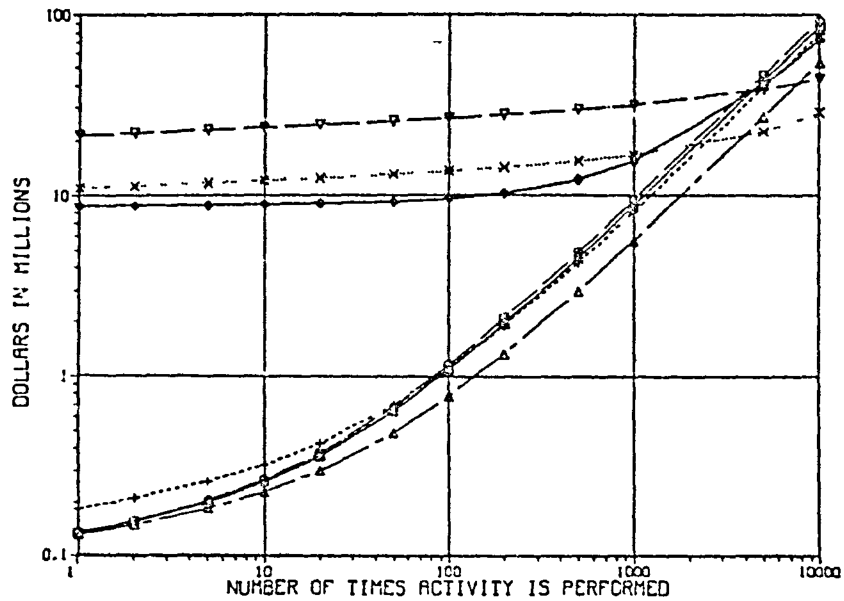
ACT NUMBER 0-GENERAL CASE B TELEOPERATED CODES A1, D5, & E3
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



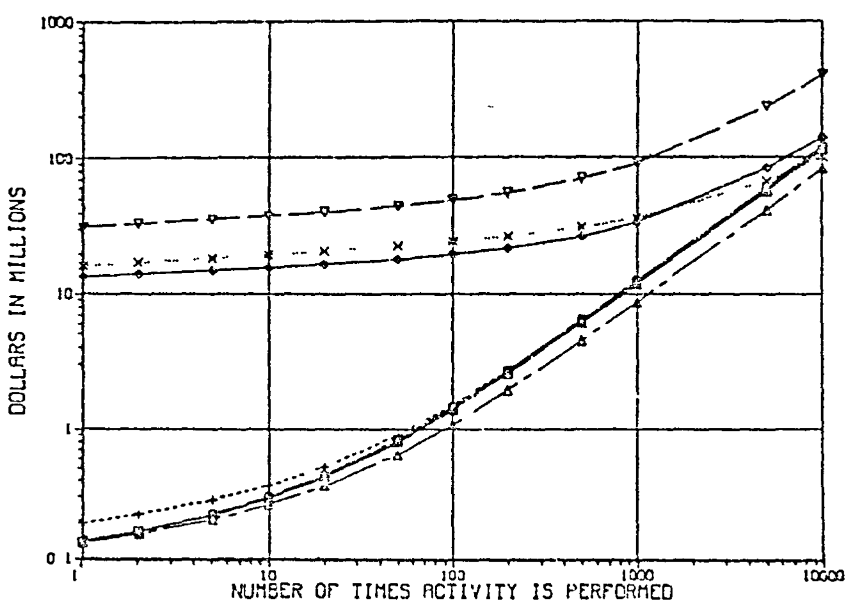
ACT NUMBER 0-GENERAL CASE B TELEOPERATED CODES A1, D5, & E3
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS



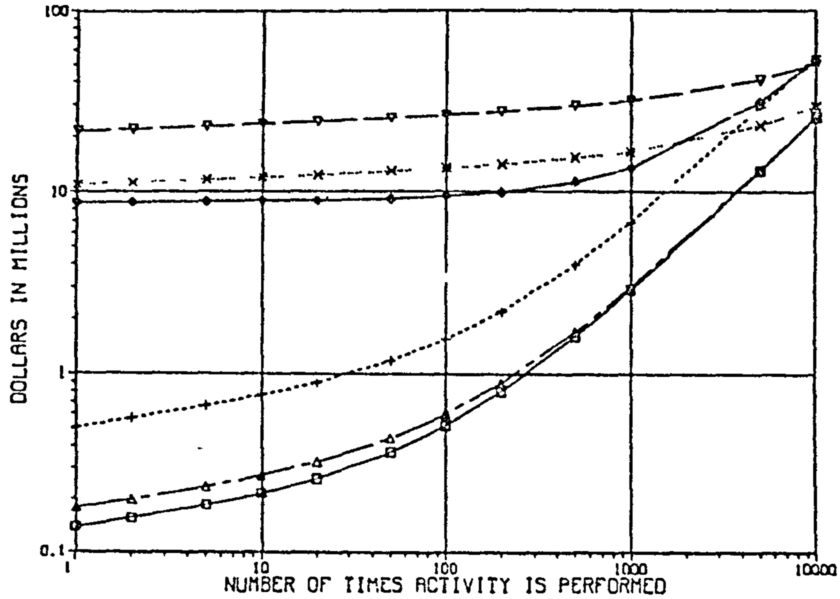
ACT NUMBER 0-GENERAL CASE C TELEOPERATED CODES A1, D5, & B3
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



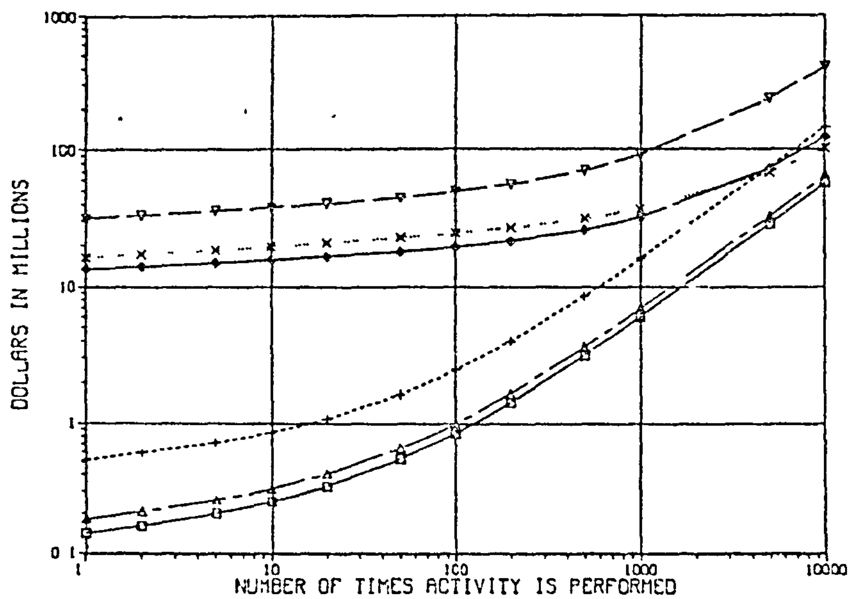
ACT NUMBER 0-GENERAL CASE C TELEOPERATED CODES A1, D5, & B3
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS



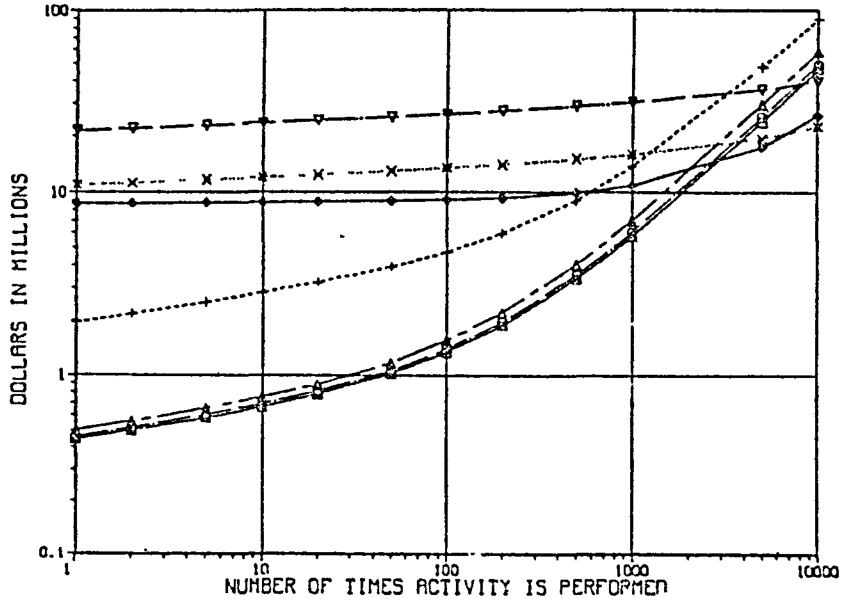
ACTIVITY NUMBER 1-ACTIVATE/INITIATE SYSTEM OPERATION
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



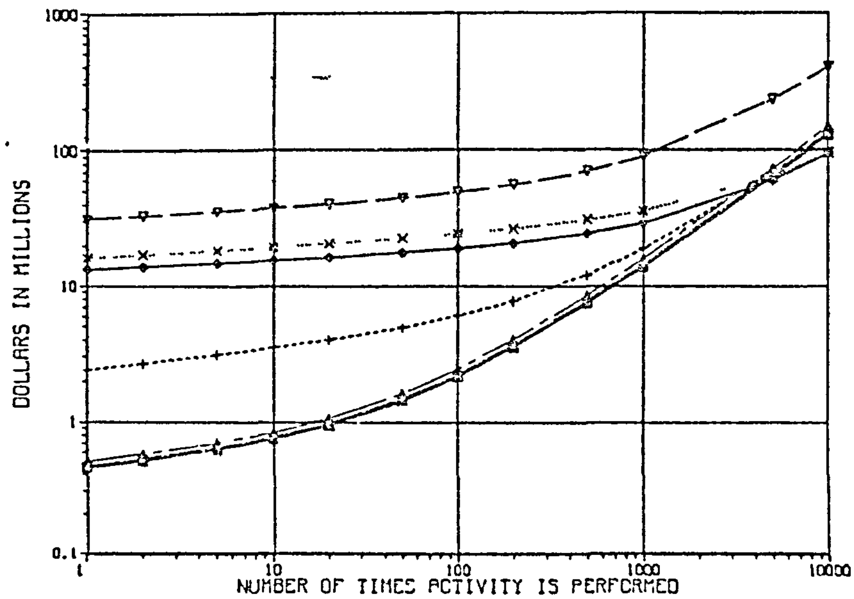
ACTIVITY NUMBER 1-ACTIVATE/INITIATE SYSTEM OPERATION
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS



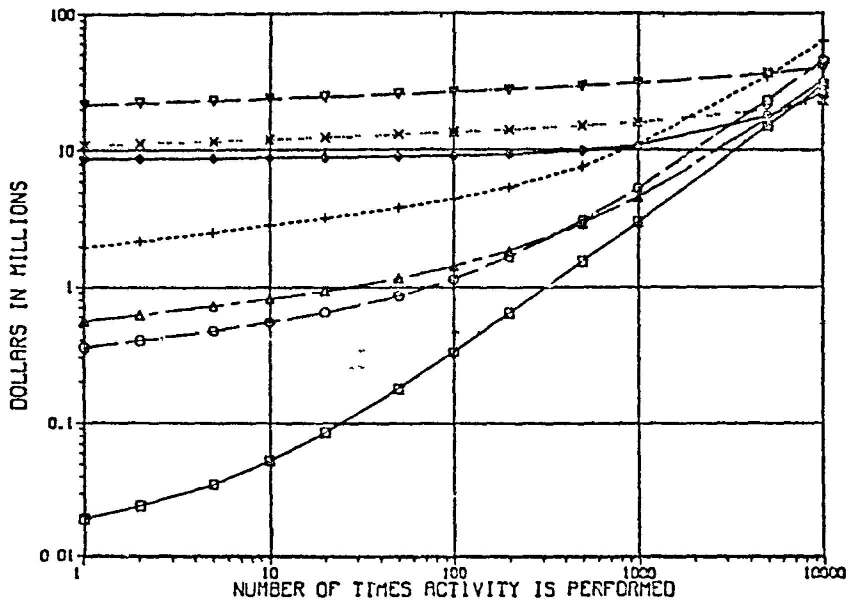
ACTIVITY NUMBER 2-ADJUST/ALIGN ELEMENTS
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



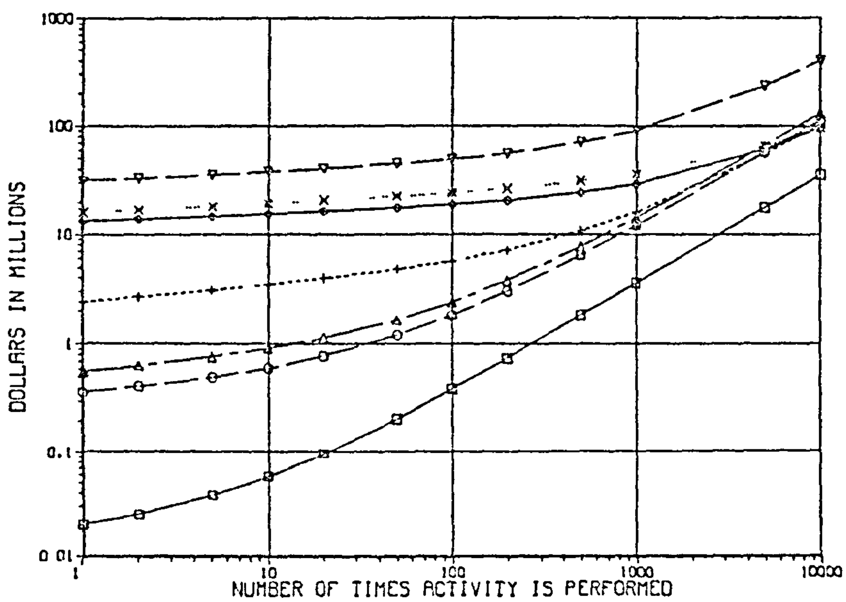
ACTIVITY NUMBER 2-ADJUST/ALIGN ELEMENTS
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS



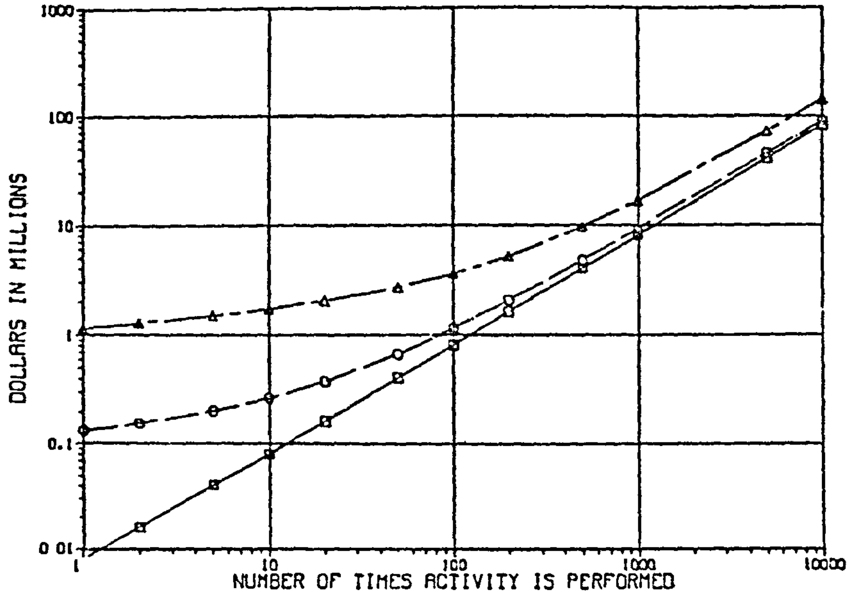
ACTIVITY NUMBER 3-ALLOCATE/ASSIGN/DISTRIBUTE
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



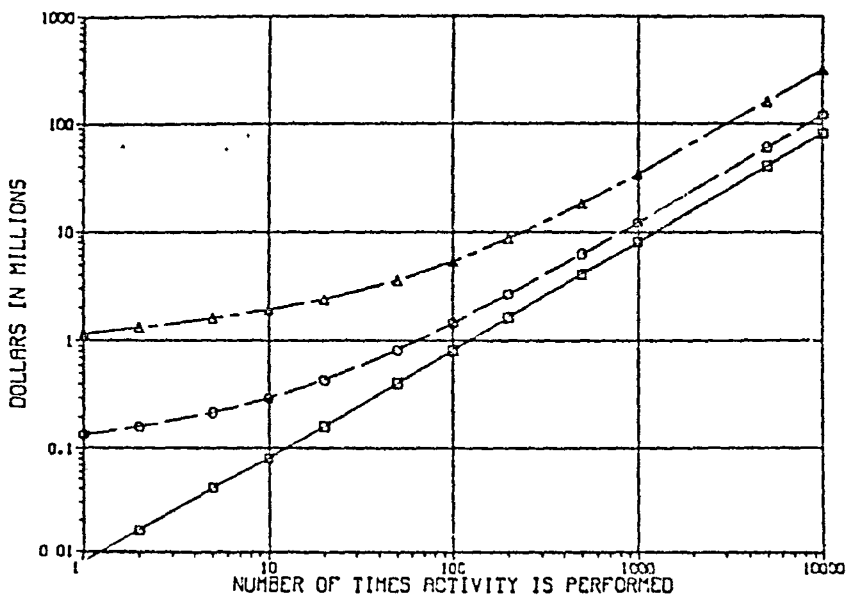
ACTIVITY NUMBER 3-ALLOCATE/ASSIGN/DISTRIBUTE
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS



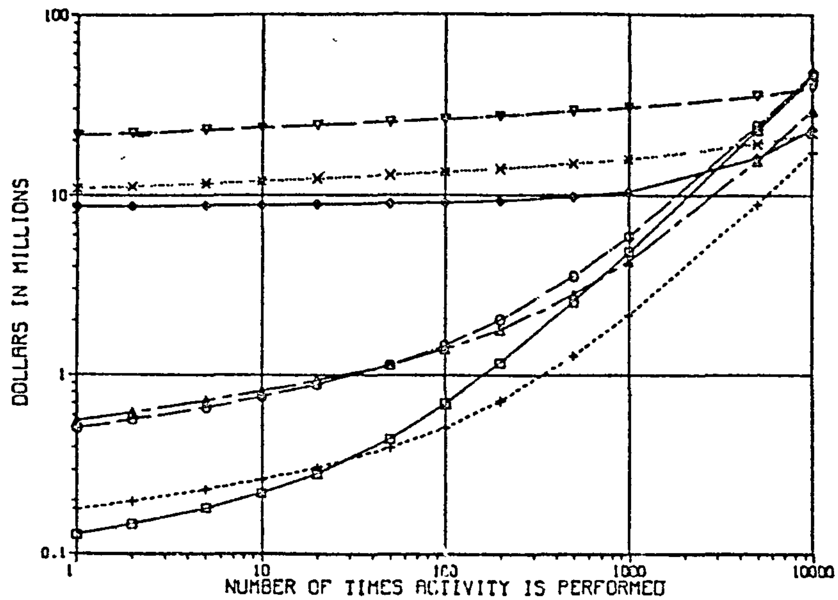
ACTIVITY NUMBER 4-APPLY BIOMEDICAL SENSOR
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



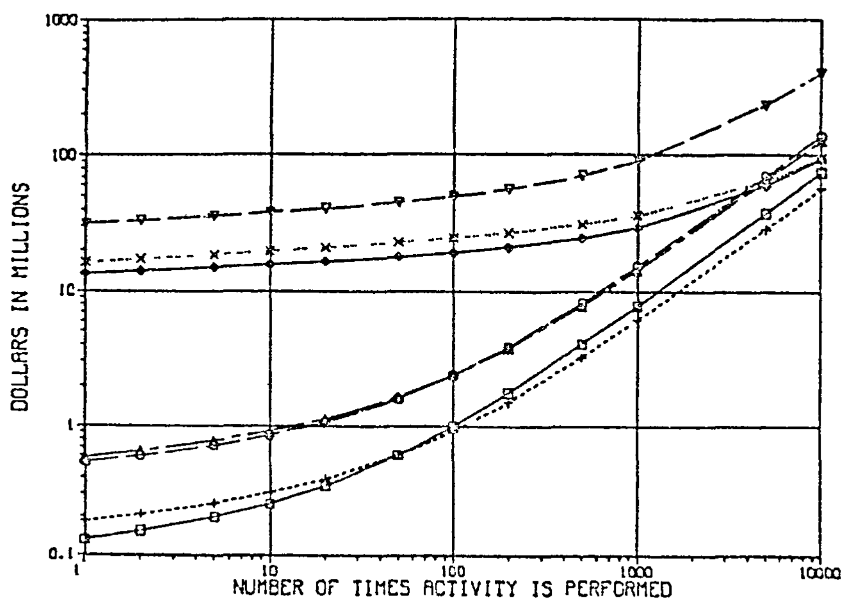
ACTIVITY NUMBER 4-APPLY BIOMEDICAL SENSOR
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS



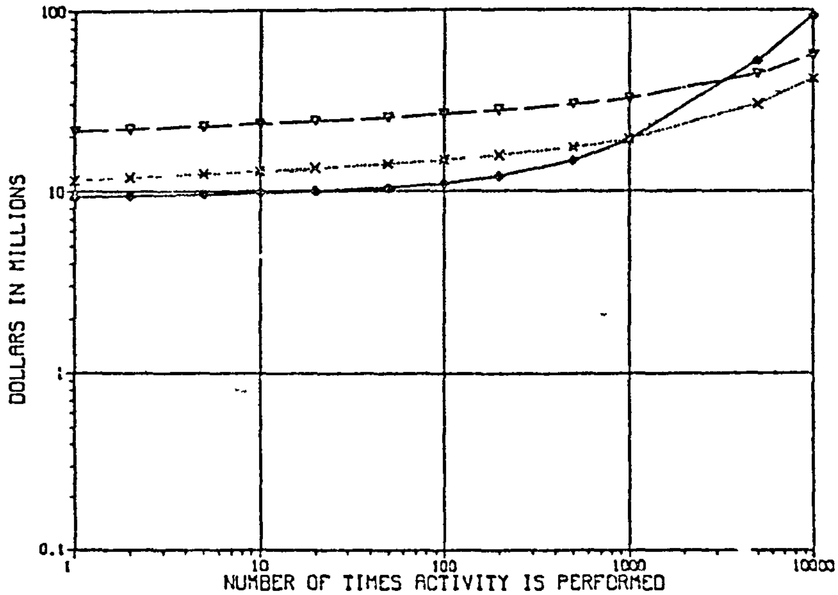
ACTIVITY NUMBER 5-COMMUNICATE INFORMATION
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



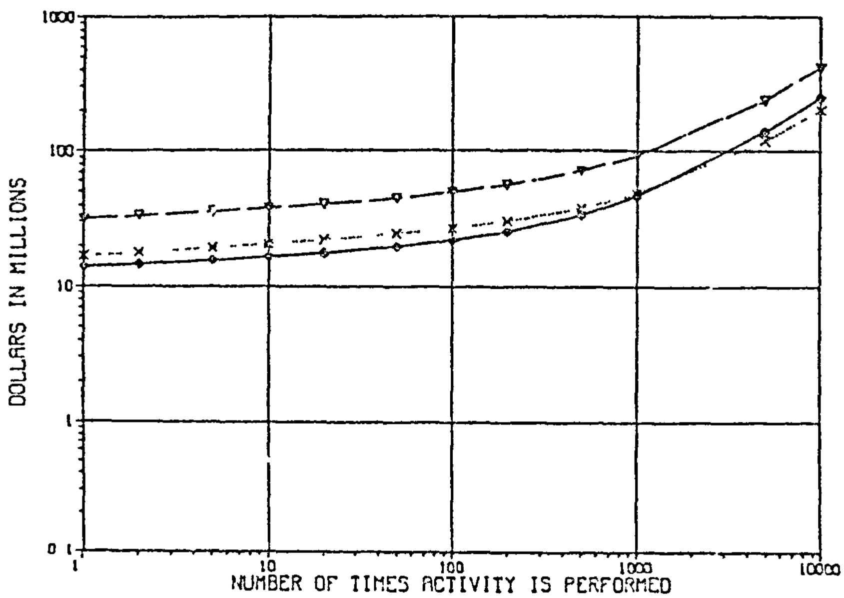
ACTIVITY NUMBER 5-COMMUNICATE INFORMATION
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS

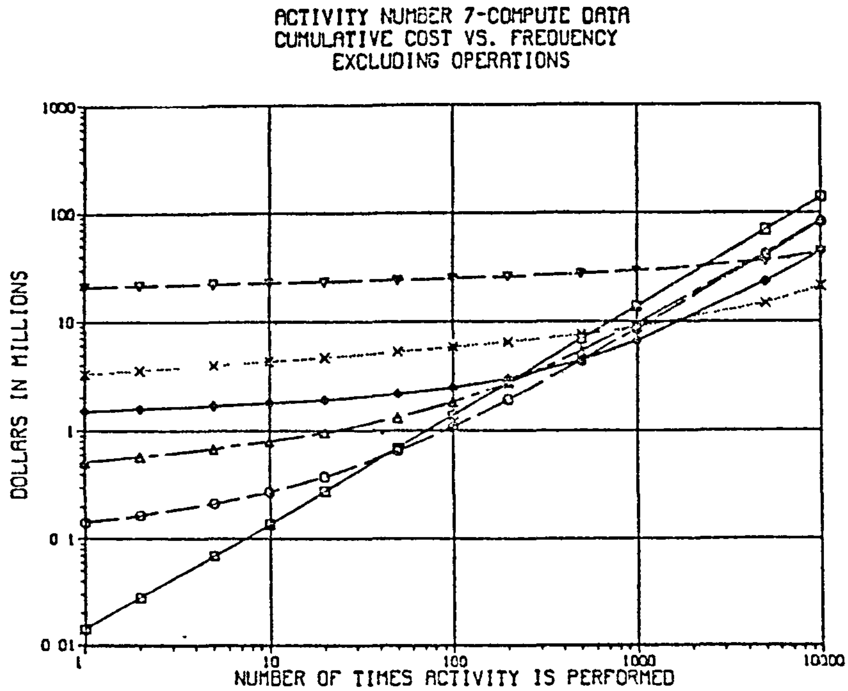


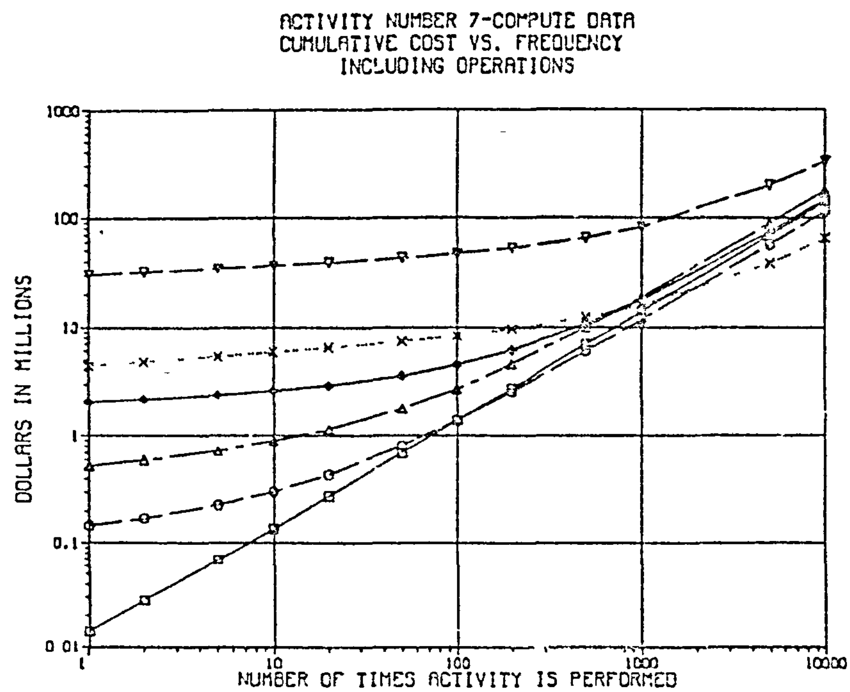
ACITIVY NUMBER 6-COMPENSATORY TRACKING
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS

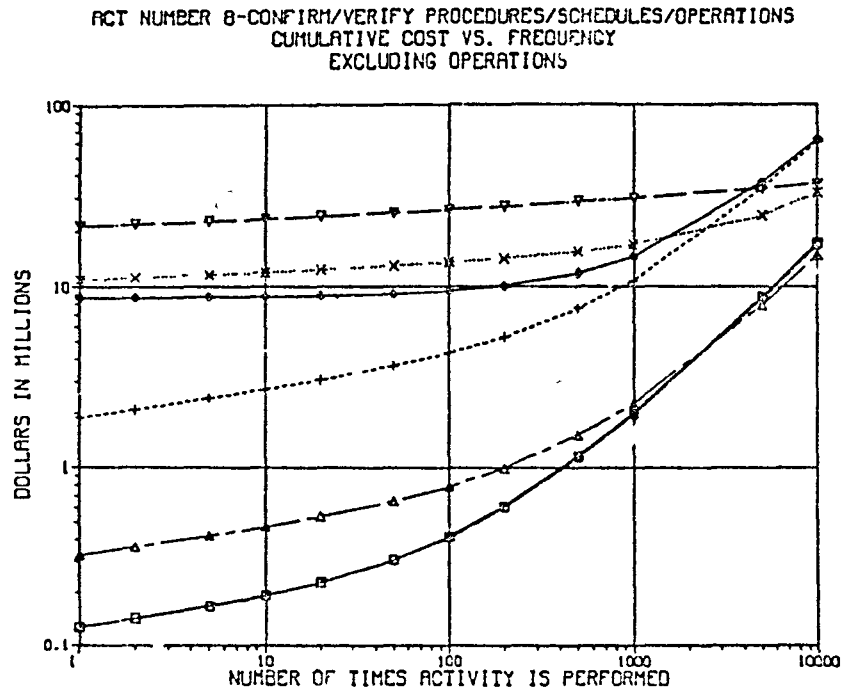


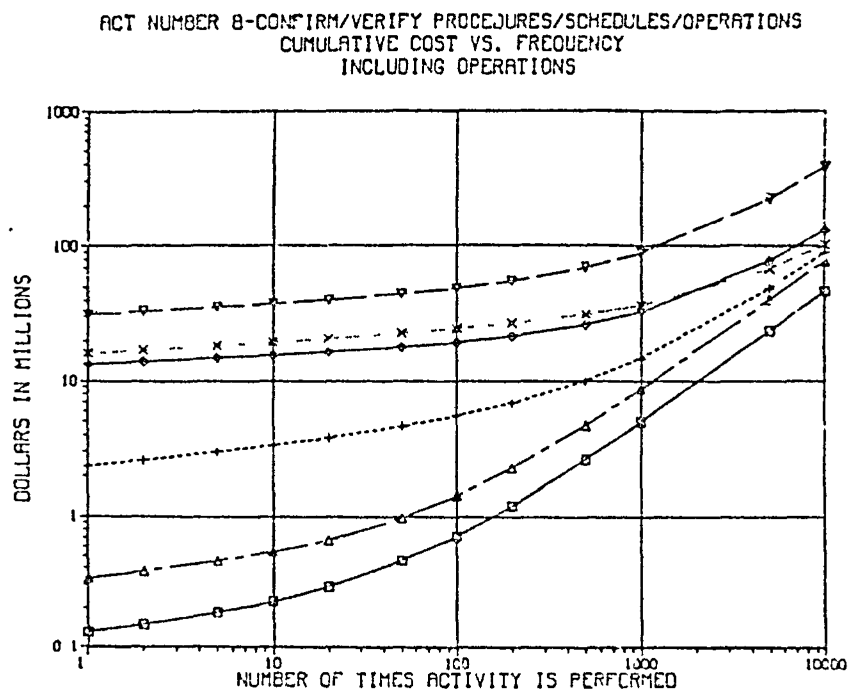
ACITIVY NUMBER 6-COMPENSATORY TRACKING
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS



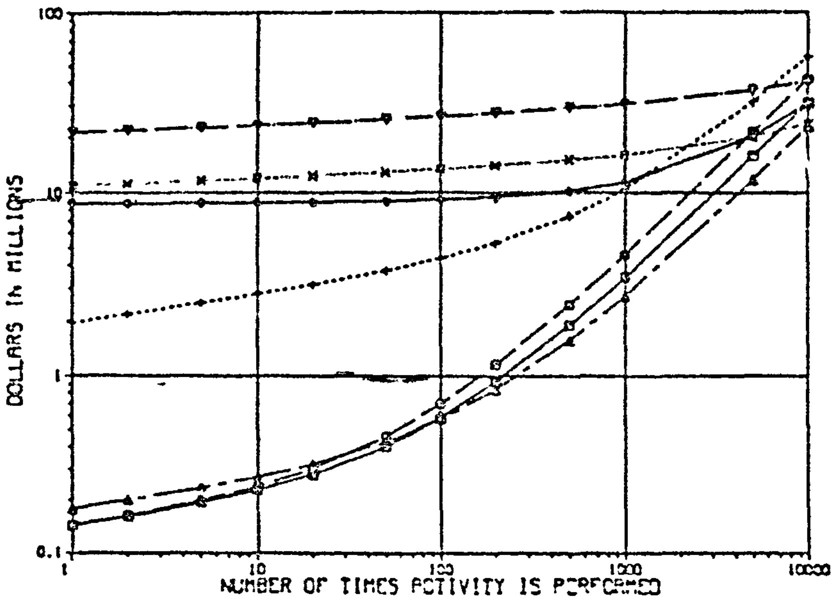

ACTIVITY NUMBER 7-COMPUTE DATA
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS
1000
100
10
1
0.1
0.01
DOLLARS IN MILLIONS
1
10
100
1000
10000
NUMBER OF TIMES ACTIVITY IS PERFORMED


ACTIVITY NUMBER 7-COMPUTE DATA
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS
1000
100
10
1
0.1
0.01
DOLLARS IN MILLIONS
1
10
100
1000
10000
NUMBER OF TIMES ACTIVITY IS PERFORMED

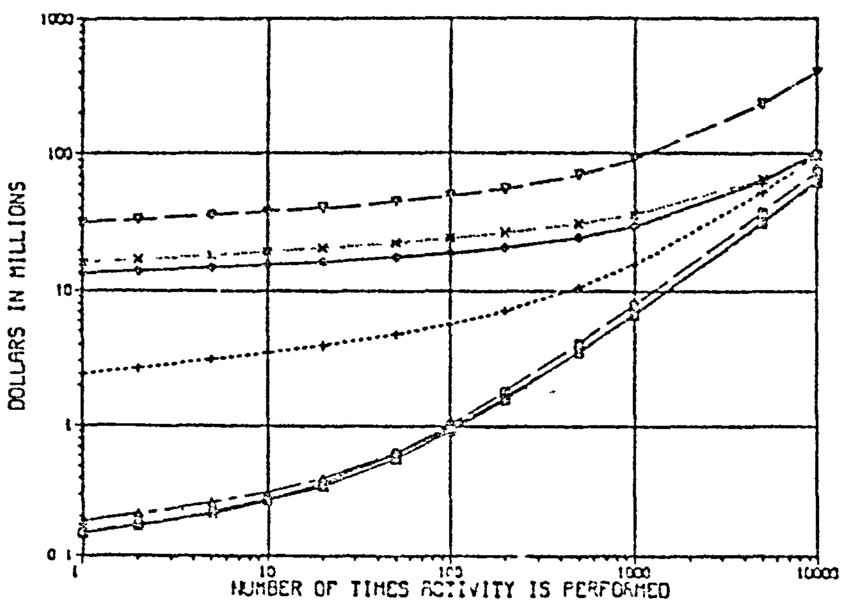

ACT NUMBER 8-CONFIRM/VERIFY PROCEDURES/SCHEDULES/OPERATIONS
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS
DOLLARS IN MILLIONS
100
10
1
0.1
1
10
100
1000
10000
NUMBER OF TIMES ACTIVITY IS PERFORMED


ACT NUMBER 8-CONFIRM/VERIFY PROCEDURES/SCHEDULES/OPERATIONS
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS
DOLLARS IN MILLIONS
1000
100
10
1
0.1
1
10
100
1000
10000
NUMBER OF TIMES ACTIVITY IS PERFORMED

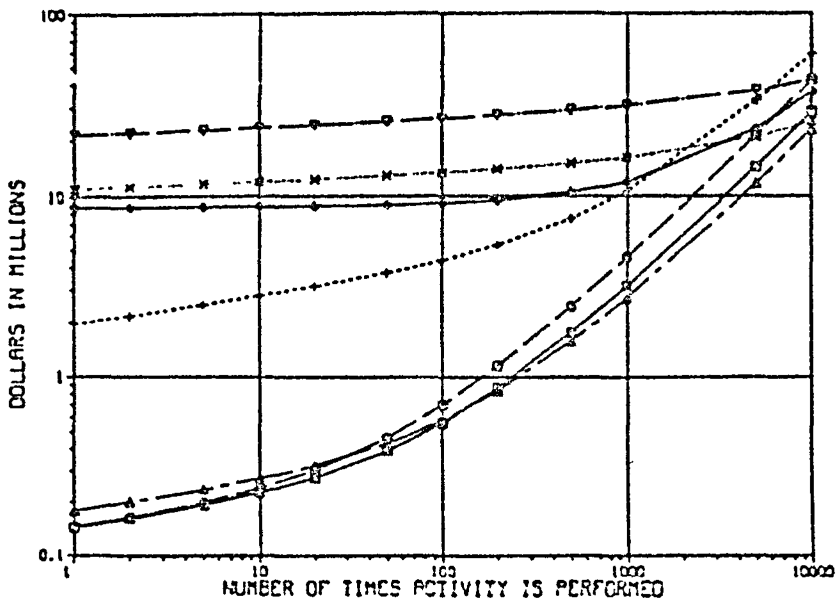
ACTIVITY NUMBER 9-CONNECT/DISCONNECT ELECTRICAL INTERFACE
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



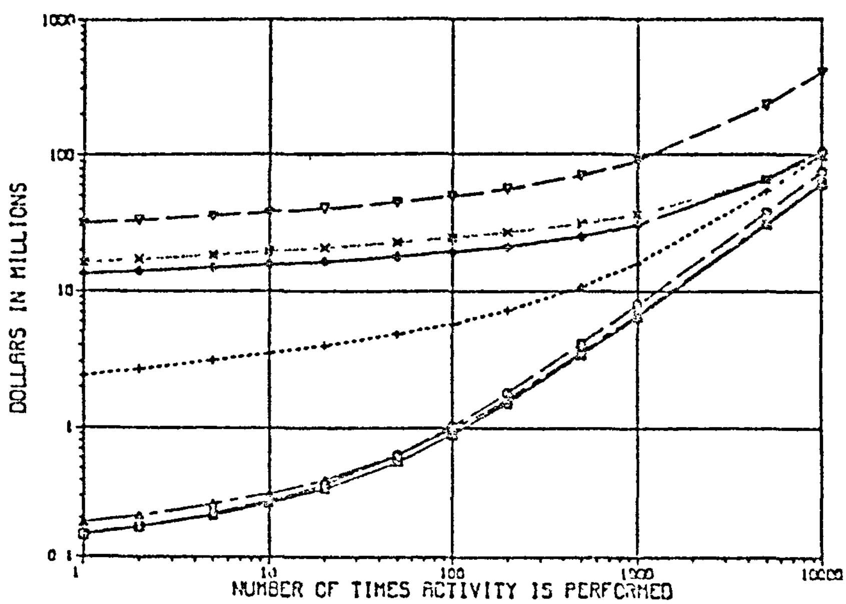
ACTIVITY NUMBER 9-CONNECT/DISCONNECT ELECTRICAL INTERFACE
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS



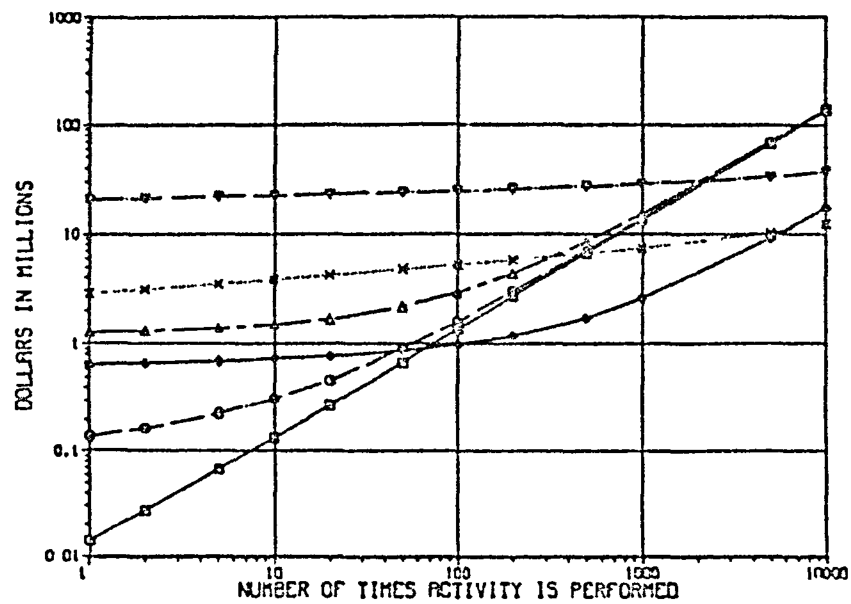
ACTIVITY NUMBER 10-CONNECT/DISCONNECT FLUID INTERFACE
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



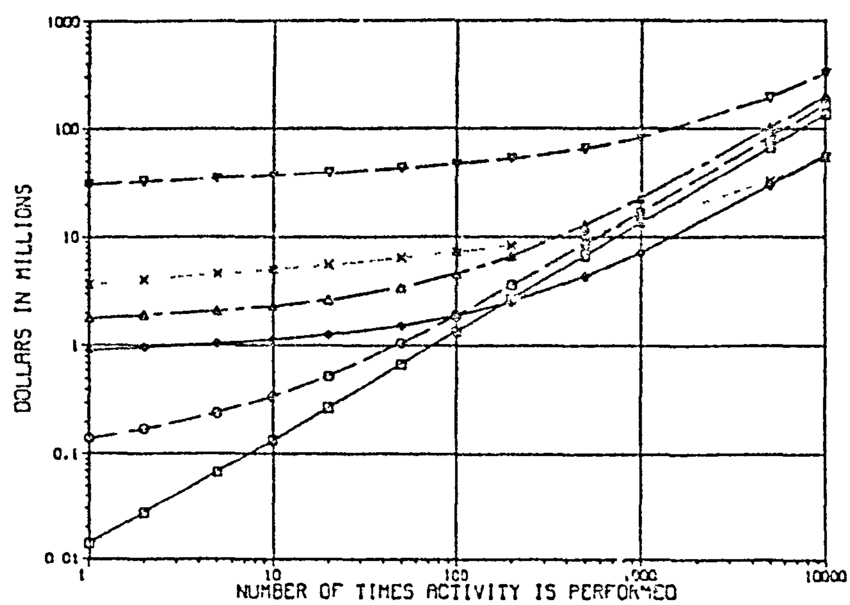
ACTIVITY NUMBER 10-CONNECT/DISCONNECT FLUID INTERFACE
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS



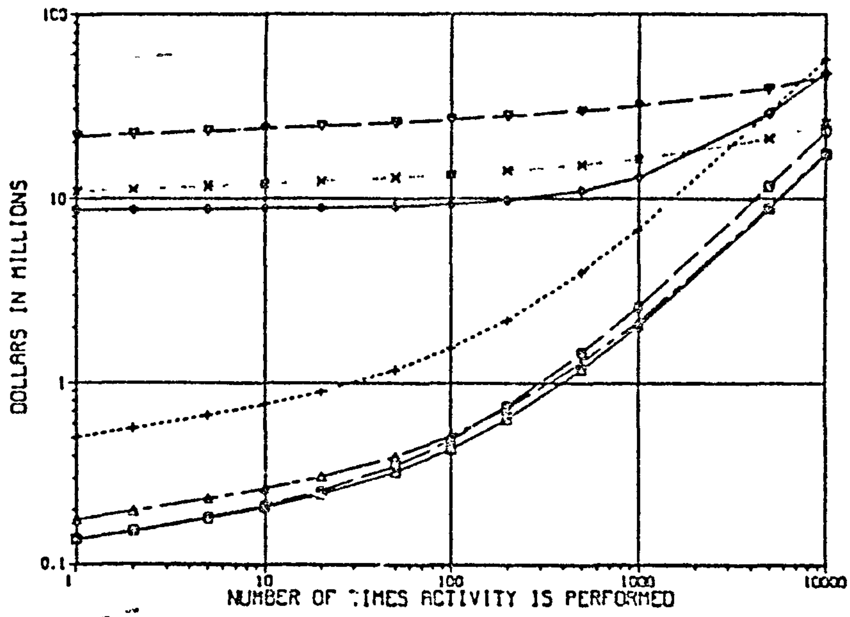
ACTIVITY NUMBER 11-CORRELATE DATA
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



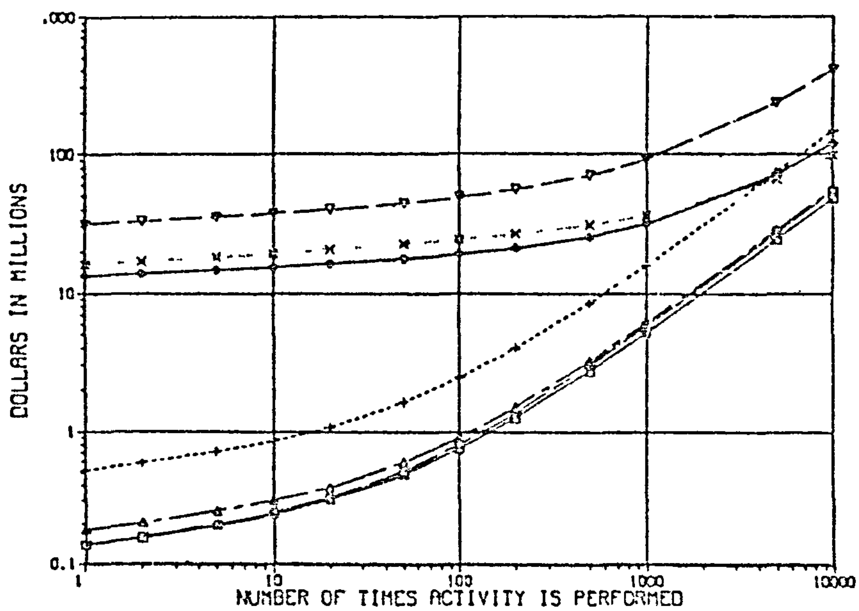
ACTIVITY NUMBER 11-CORRELATE DATA
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERTIONS



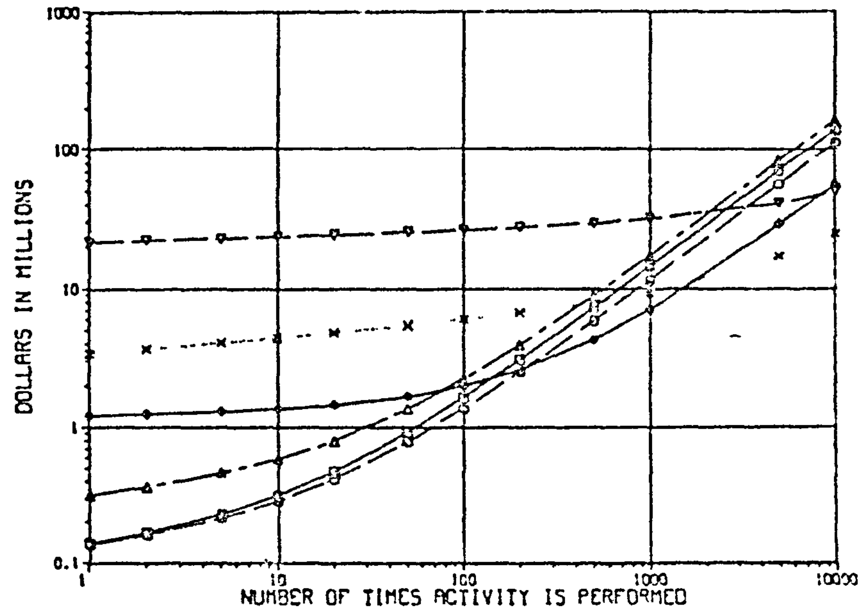
ACTIVITY NUMBER 12-DEACTIVATE/TERMINATE SYSTEM OPERATION
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



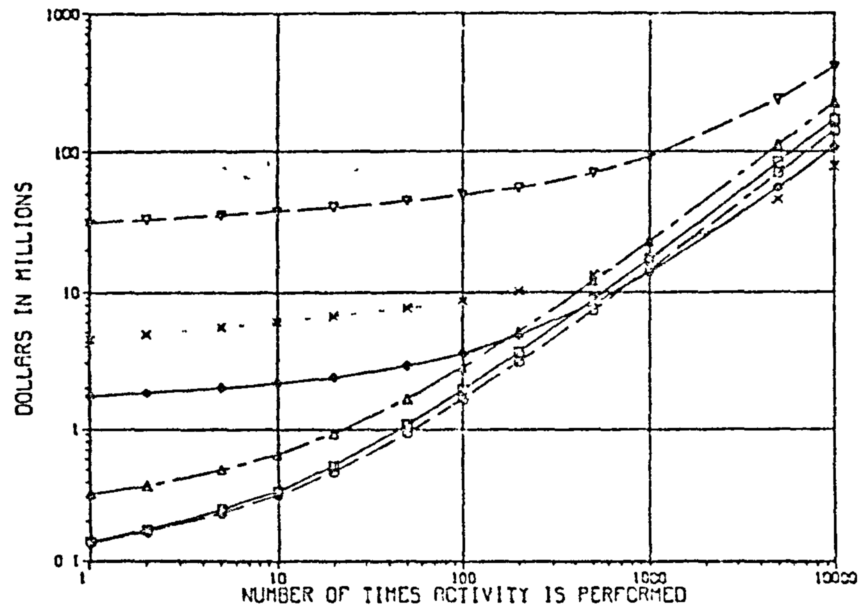
ACTIVITY NUMBER 12-DEACTIVATE/TERMINATE SYSTEM OPERATION
CUMULATIVE COST VS FREQUENCY
INCLUDING OPERATIONS



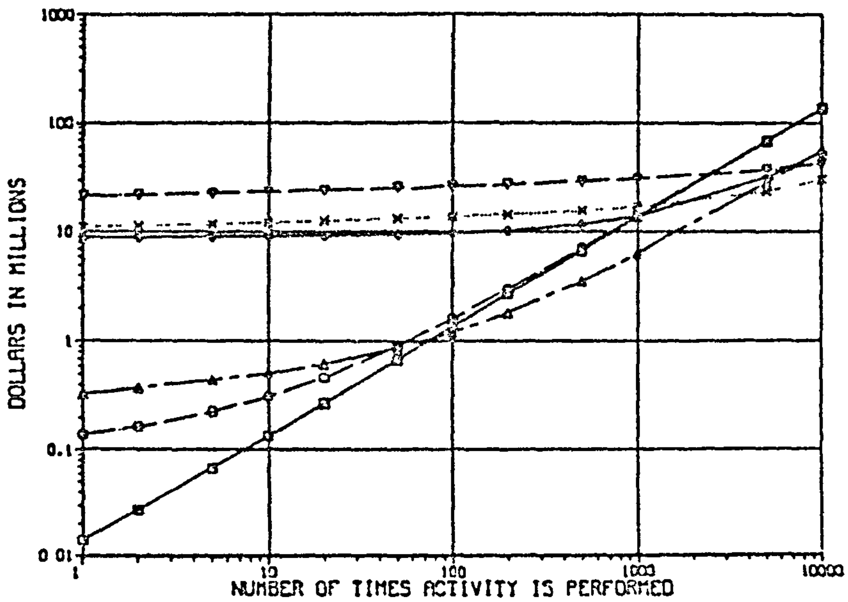
ACTIVITY NUMBER 13-DECODE/ENCODE DATA
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



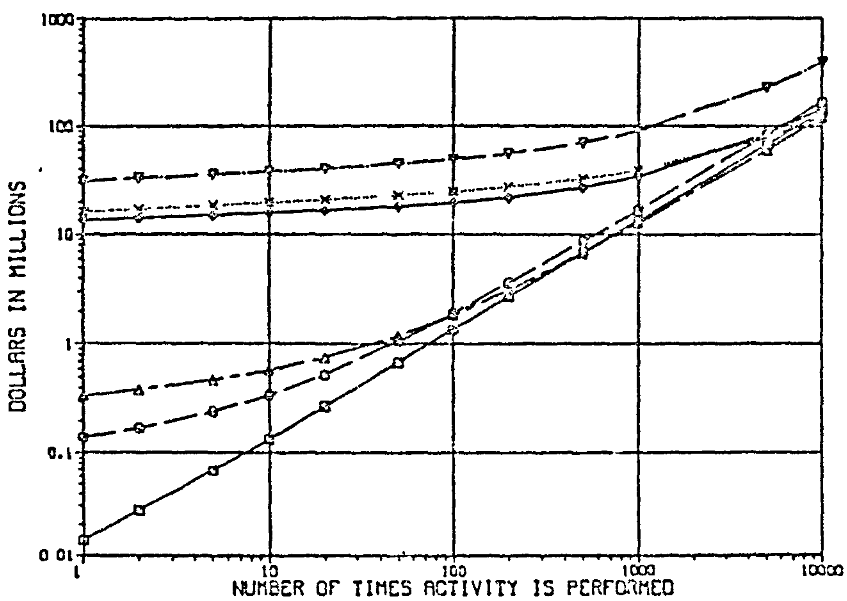
ACTIVITY NUMBER 13-DECODE/ENCODE DATA
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS



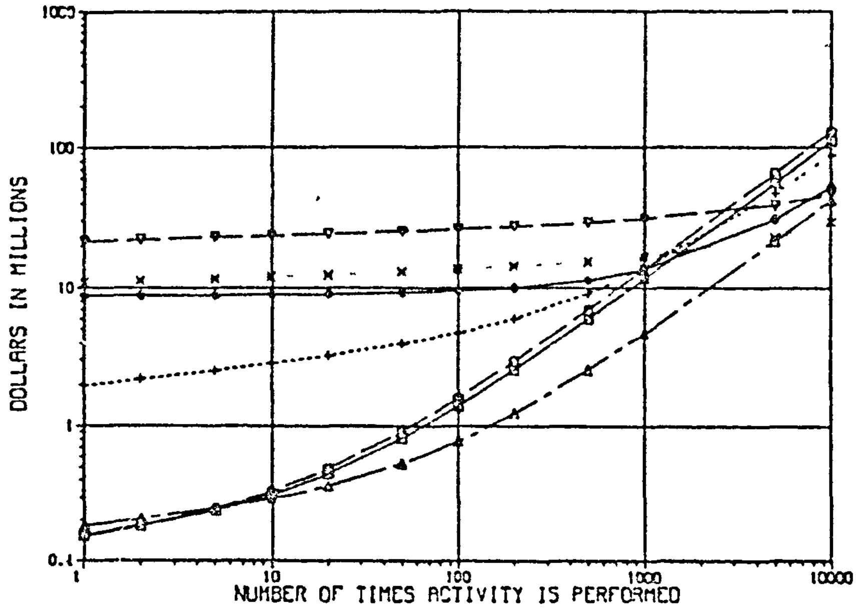
ACTIVITY NUMBER 14-DEFINE PROCEDURES/SCHEDULES/OPERATIONS
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



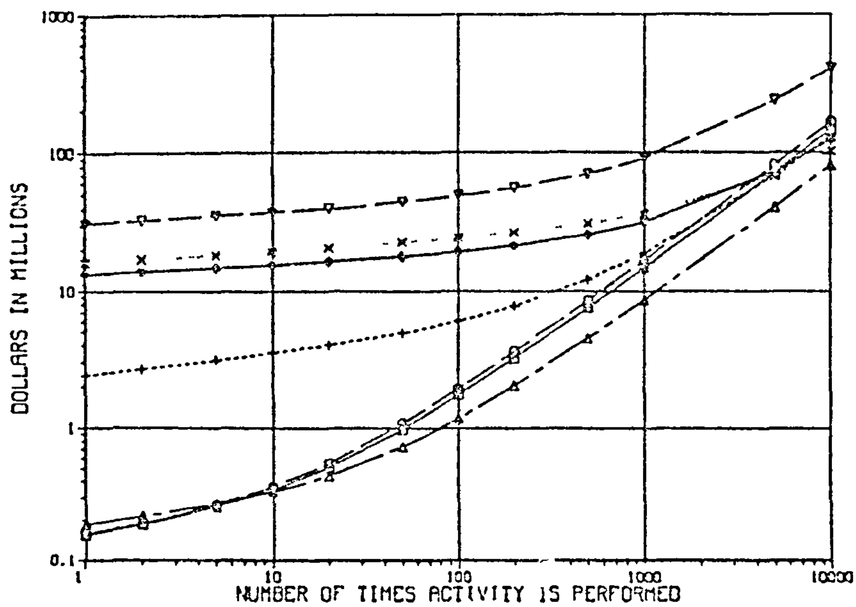
ACTIVITY NUMBER 14-DEFINE PROCEDURES/SCHEDULES/OPERATIONS
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERAIONS



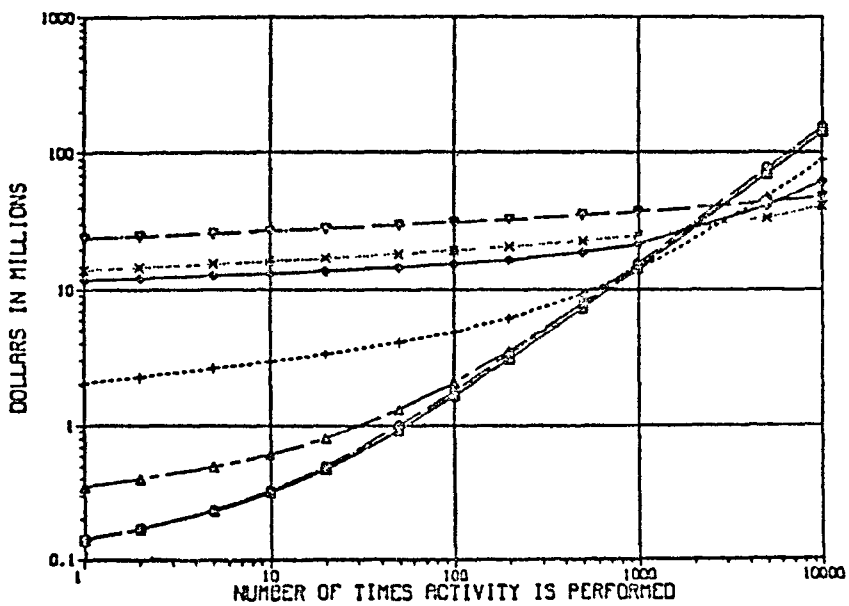
ACTIVITY NUMBER 15-DEPLOY/RETRACT APPENDAGE
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



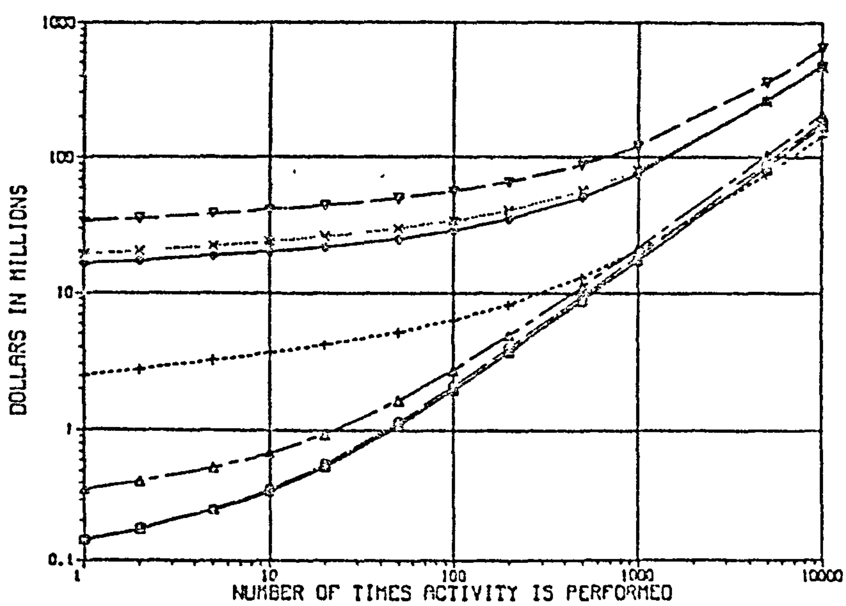
ACTIVITY NUMBER 15-DEPLOY/RETRACT APPENDAGE
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS



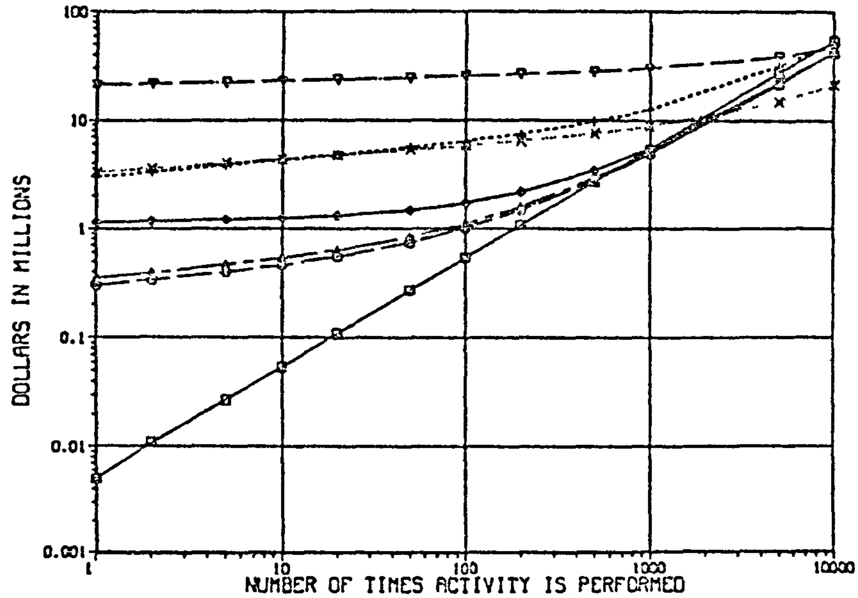
ACTIVITY NUMBER 16-DETECT CHANGE IN STATE OR CONDITION
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



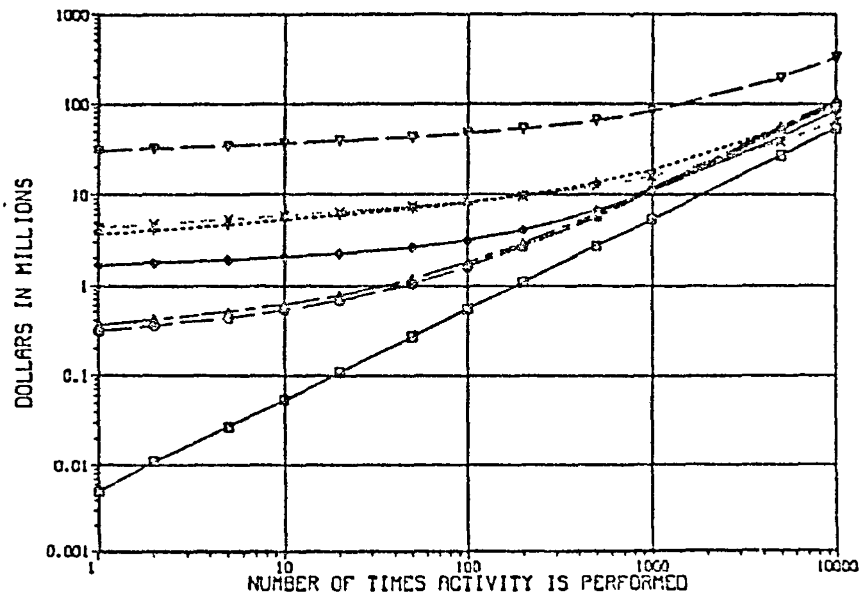
ACTIVITY NUMBER 16-DETECT CHANGE IN STATE OR CONDITION
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS



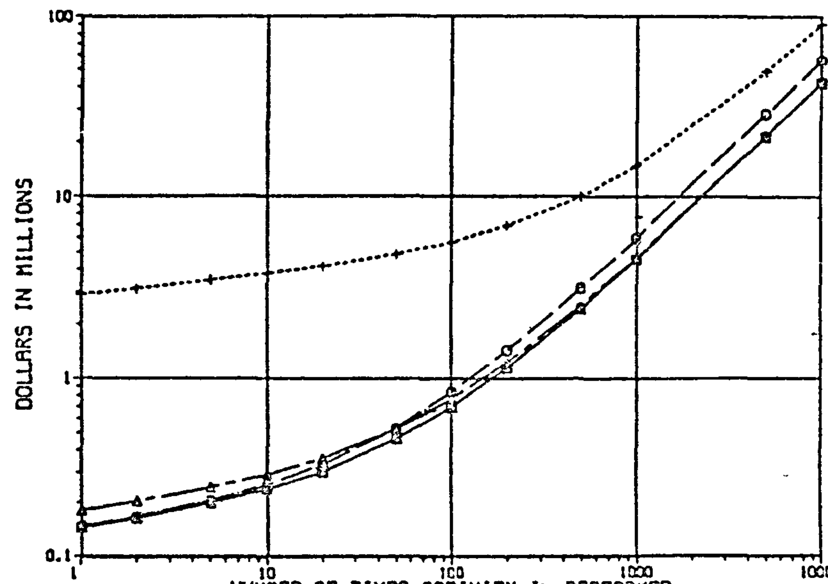
ACTIVITY NUMBER 17-DISPLAY DATA
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



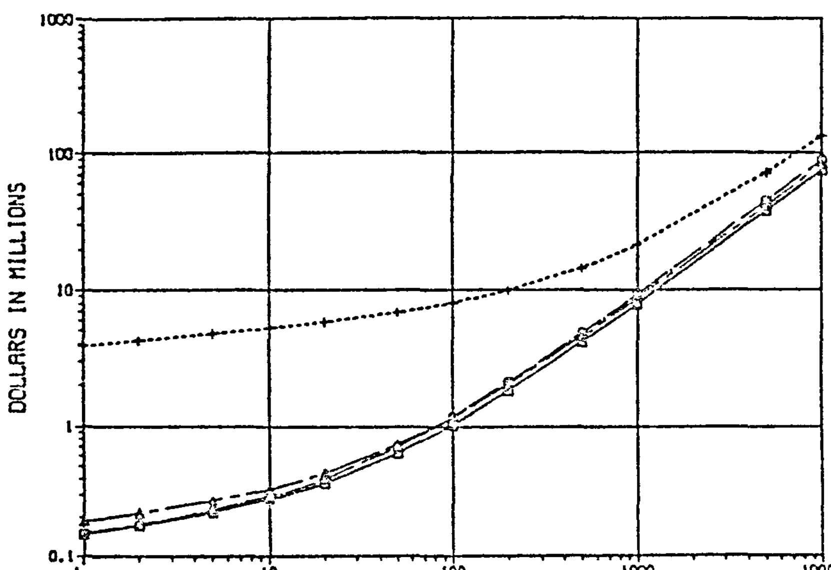
ACTIVITY NUMBER 17-DISPLAY DATA
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERAIONS



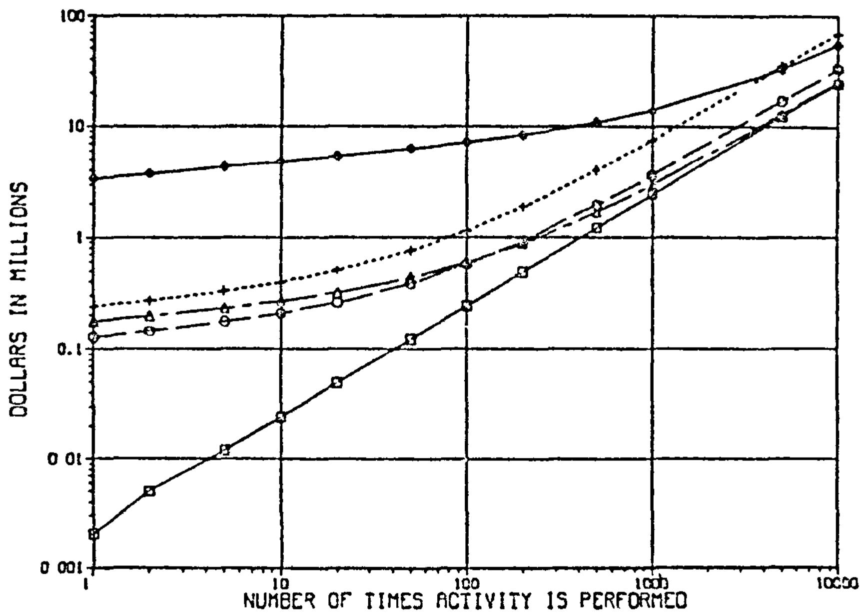
ACTIVITY NUMBER 18-GATHER/REPLACE TOOLS/EQUIPMENT
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



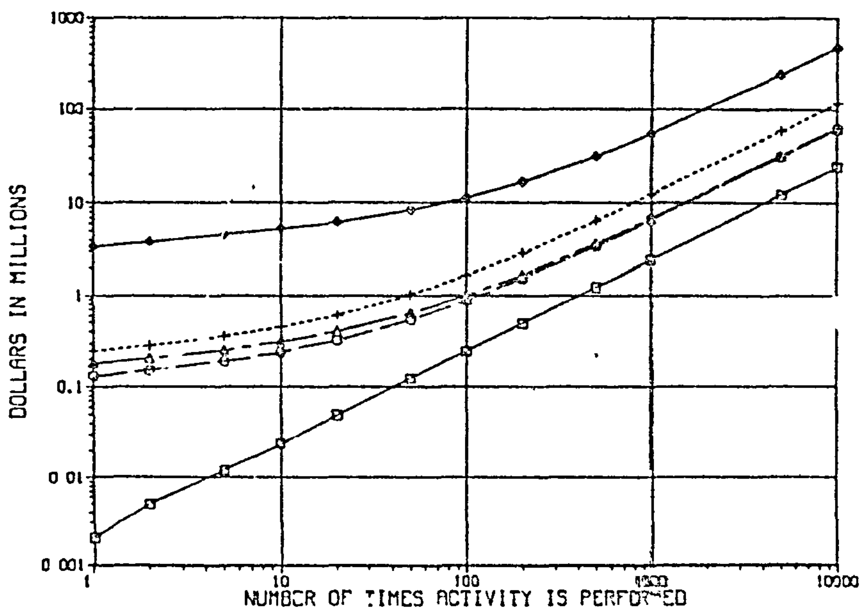
ACTIVITY NUMBER 18-GATHER/REPLACE TOOLS/EQUIPMENT
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS



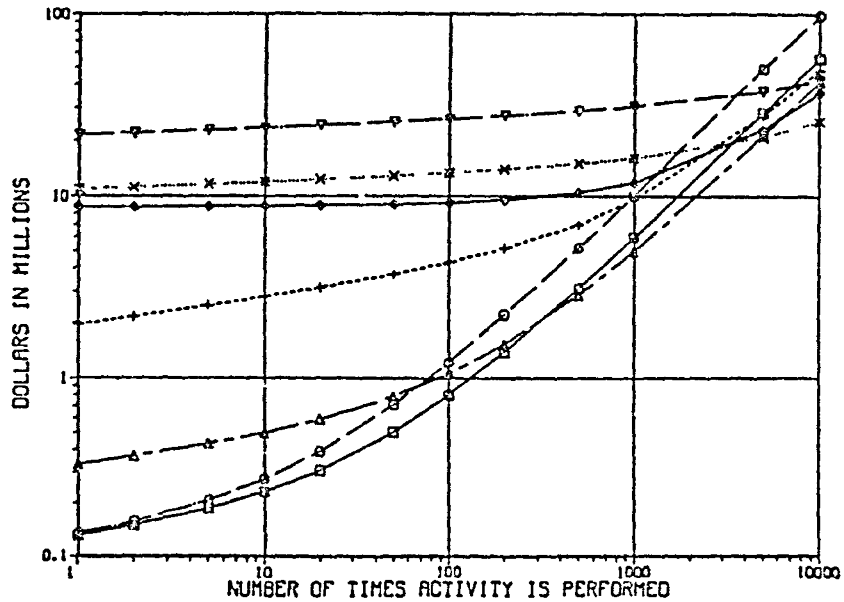
ACTIVITY NUMBER 19-HANDLE/INSPECT/EXAMINE LIVING ORGANISMS
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



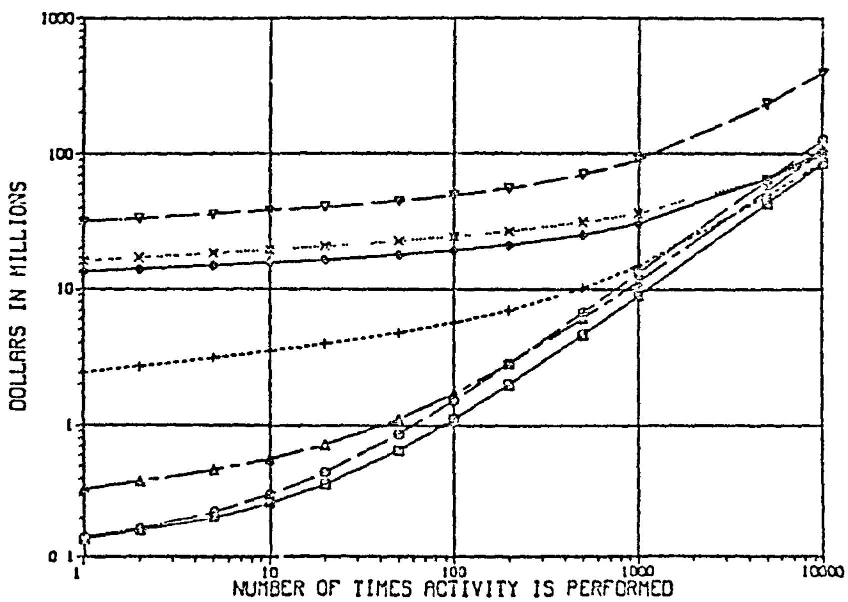
ACTIVITY NUMBER 19-HANDLE/INSPECT/EXAMINE LIVING ORGANISMS
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS

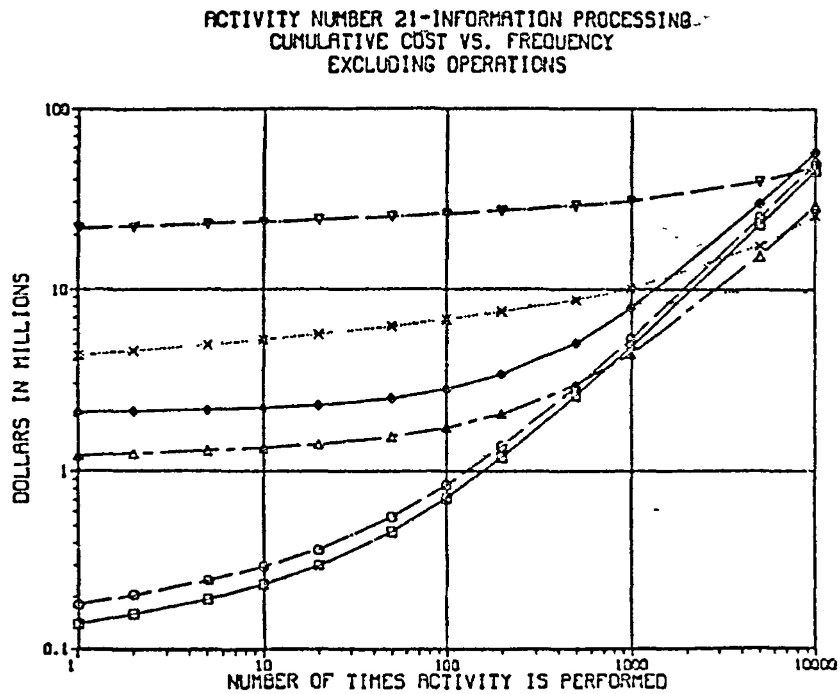


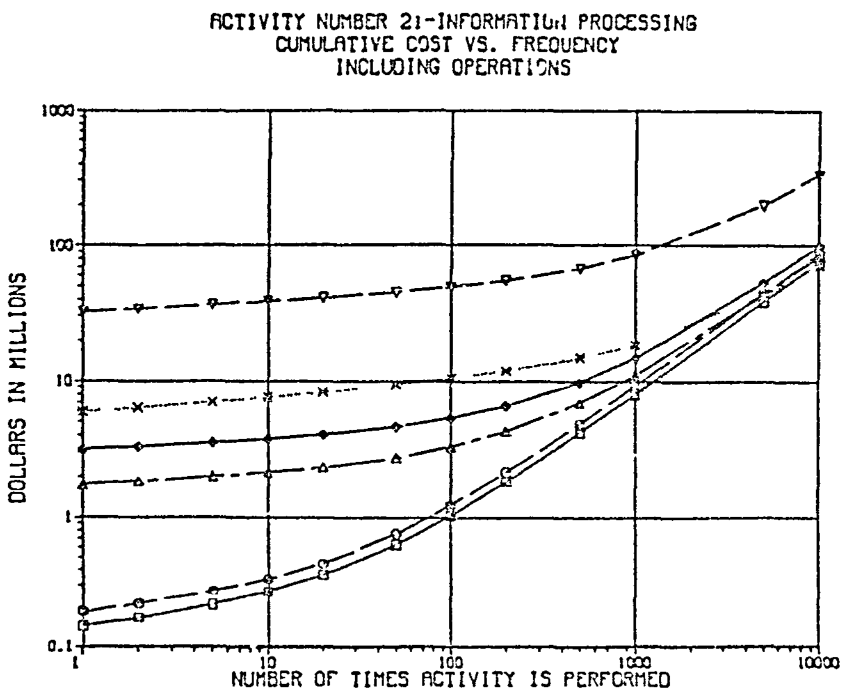
ACTIVITY NUMBER 20-IMPLEMENT PROCEDURES/SCHEDULES
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



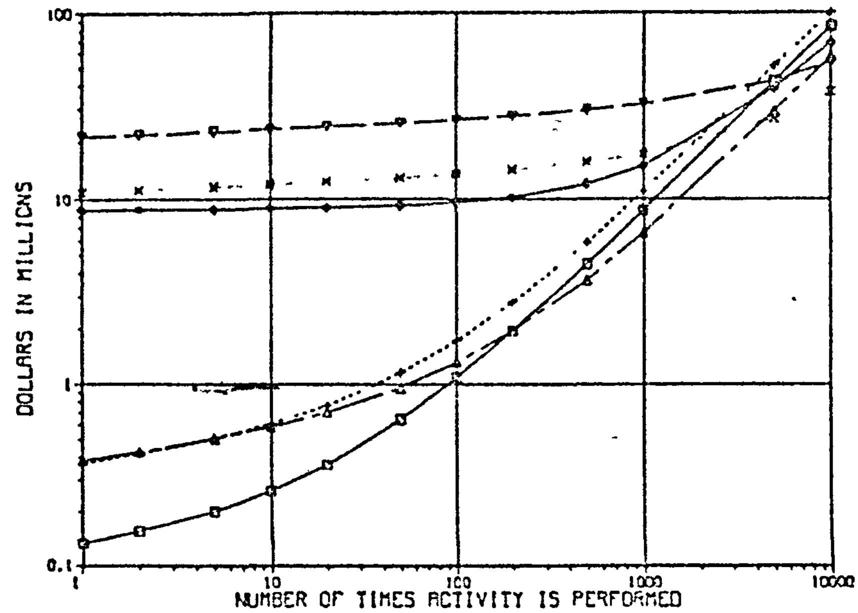
ACTIVITY NUMBER 20-IMPLEMENT PROCEDURES/SCHEDULES
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS



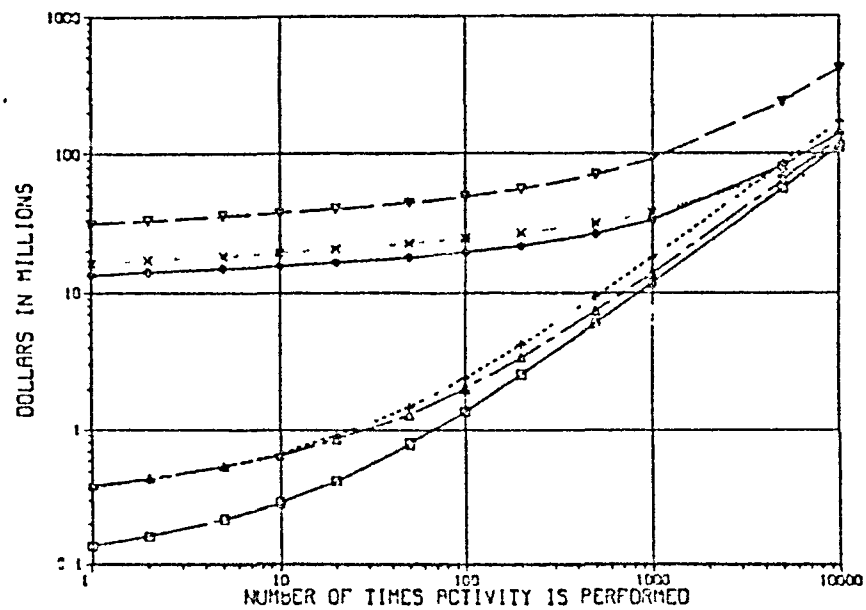

ACTIVITY NUMBER 21-INFORMATION PROCESSING
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS
DOLLARS IN MILLIONS
100
10
1
0.1
1
10
100
1000
10000
NUMBER OF TIMES ACTIVITY IS PERFORMED


ACTIVITY NUMBER 21-INFORMATION PROCESSING
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS
DOLLARS IN MILLIONS
1000
100
10
1
0.1
1
10
100
1000
10000
NUMBER OF TIMES ACTIVITY IS PERFORMED

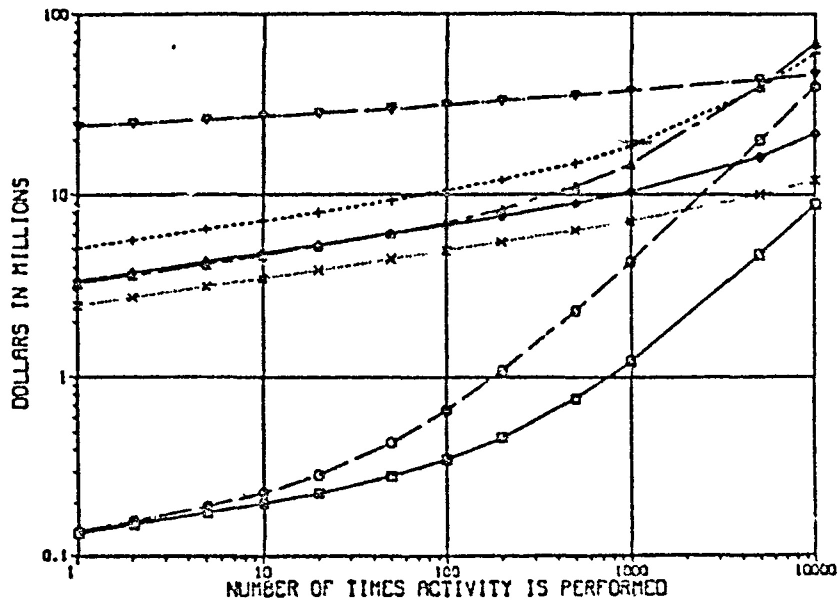
ACTIVITY NUMBER 22-INSPECT/OBSERVE
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



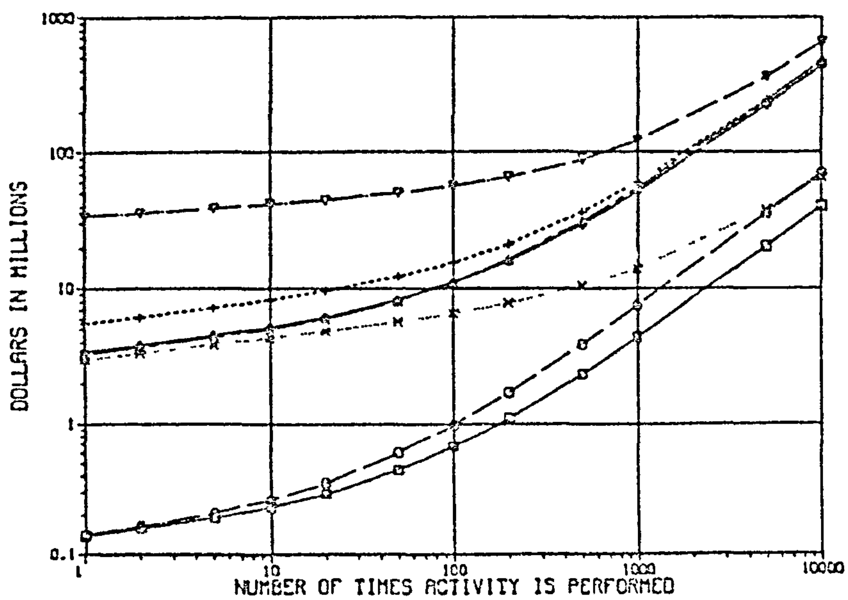
ACTIVITY NUMBER 22-INSPECT/OBSERVE
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS



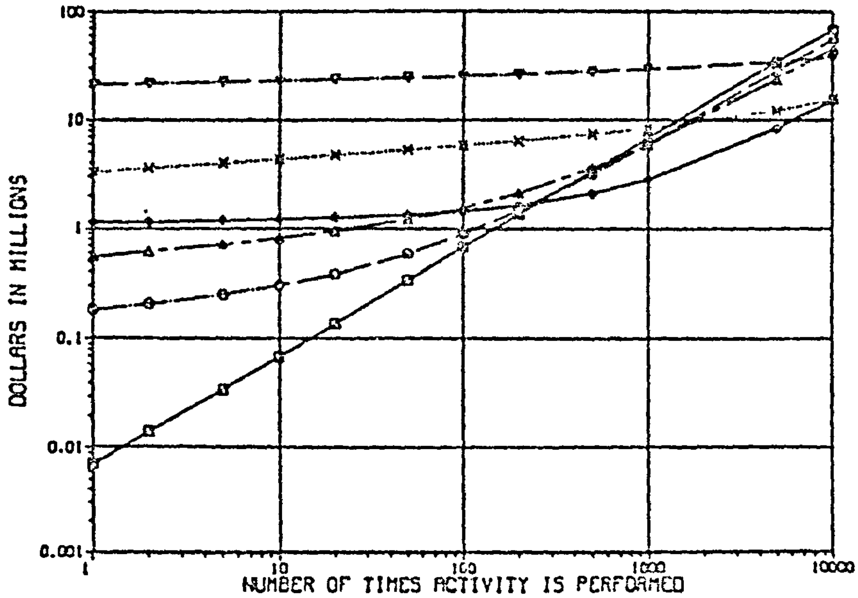
ACTIVITY NUMBER 23-MEASURE 'SCALE' PHYSICAL DIMENSIONS
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



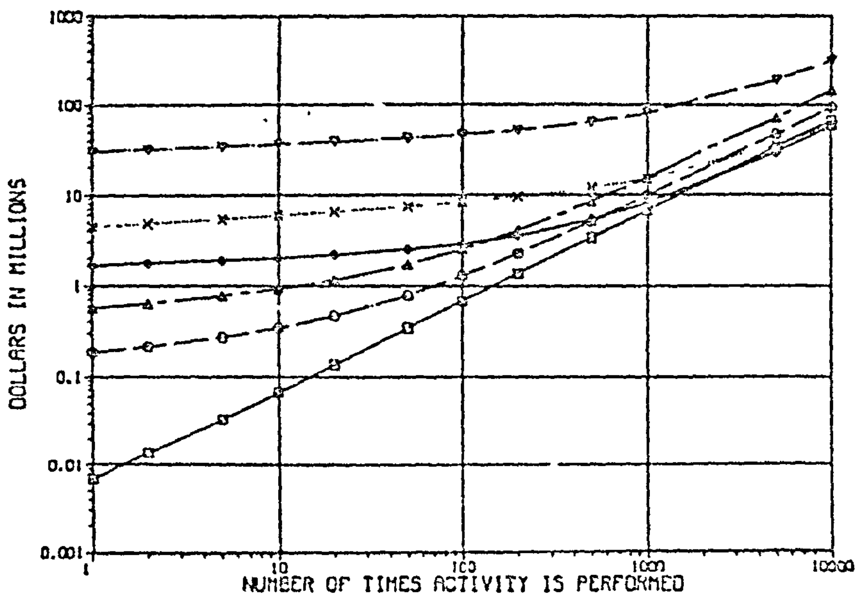
ACTIVITY NUMBER 23-MEASURE 'SCALE' PHYSICAL DIMENSIONS
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS

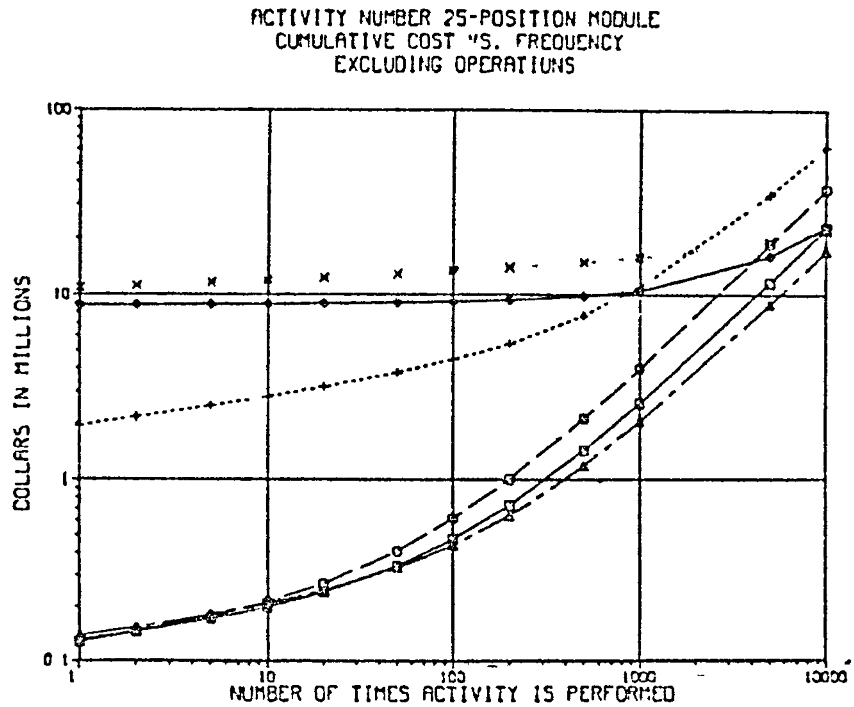


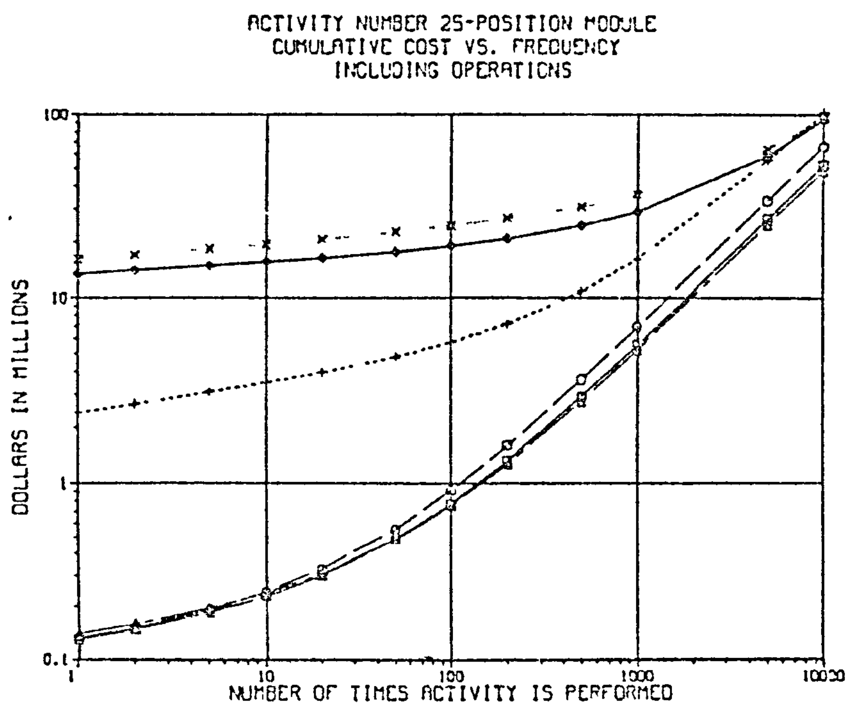
ACTIVITY NUMBER 24-PLOT DATA
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



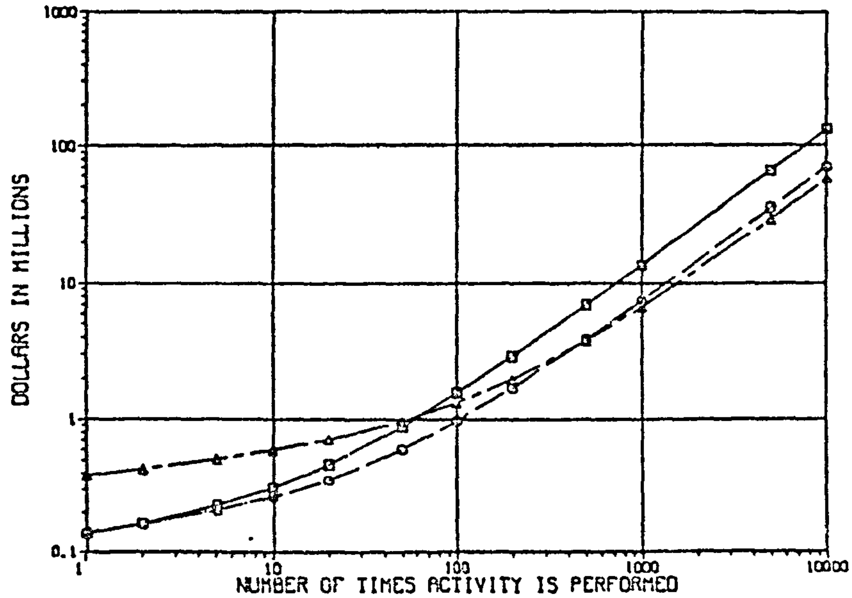
ACTIVITY NUMBER 24-PLOT DATA
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS



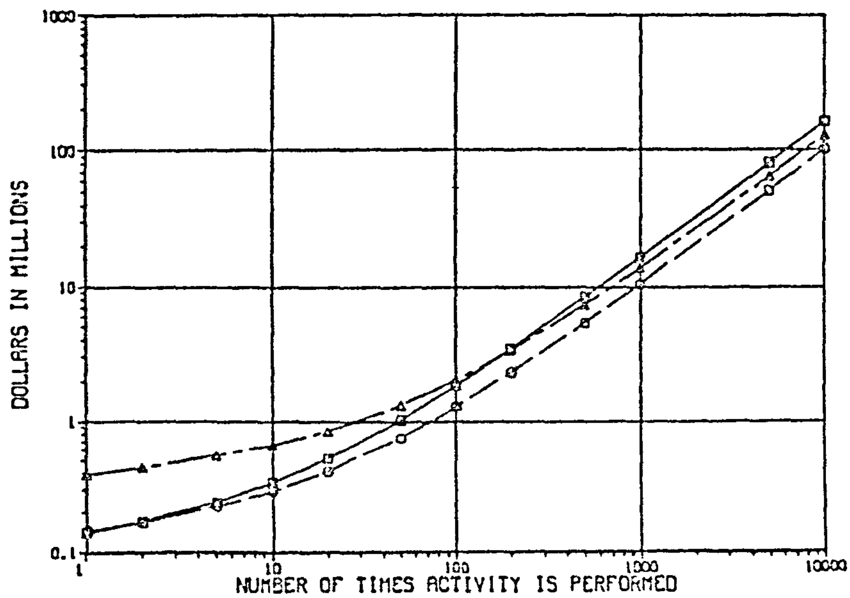

ACTIVITY NUMBER 25-POSITION MODULE
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS
100
10
1
0.1
DOLLARS IN MILLIONS
1
10
100
1000
10000
NUMBER OF TIMES ACTIVITY IS PERFORMED


ACTIVITY NUMBER 25-POSITION MODULE
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS
100
10
1
0.1
DOLLARS IN MILLIONS
1
10
100
1000
10000
NUMBER OF TIMES ACTIVITY IS PERFORMED

ACTIVITY NUMBER 26-PRECISION MANIPULATION OF OBJECTS
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS

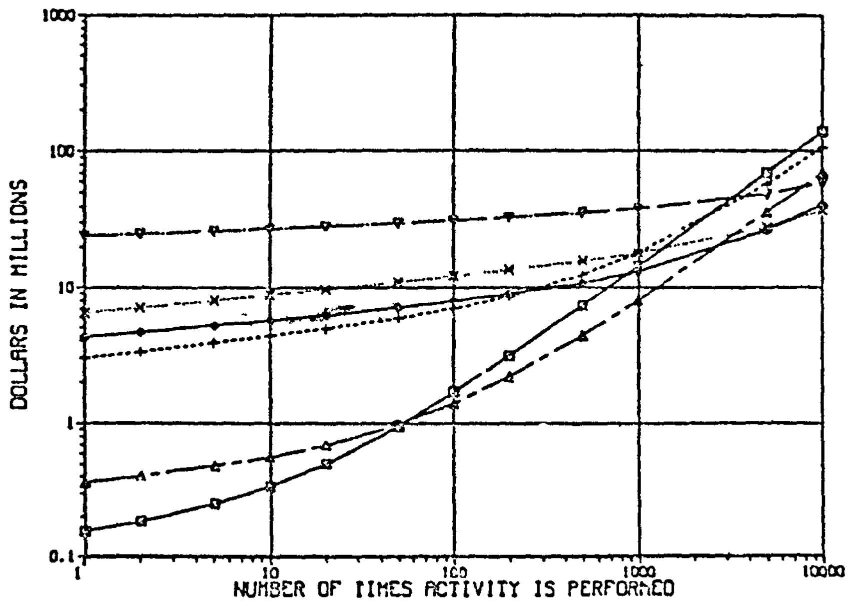


ACTIVITY NUMBER 26-PRECISION MANIPULATION OF OBJECTS
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS

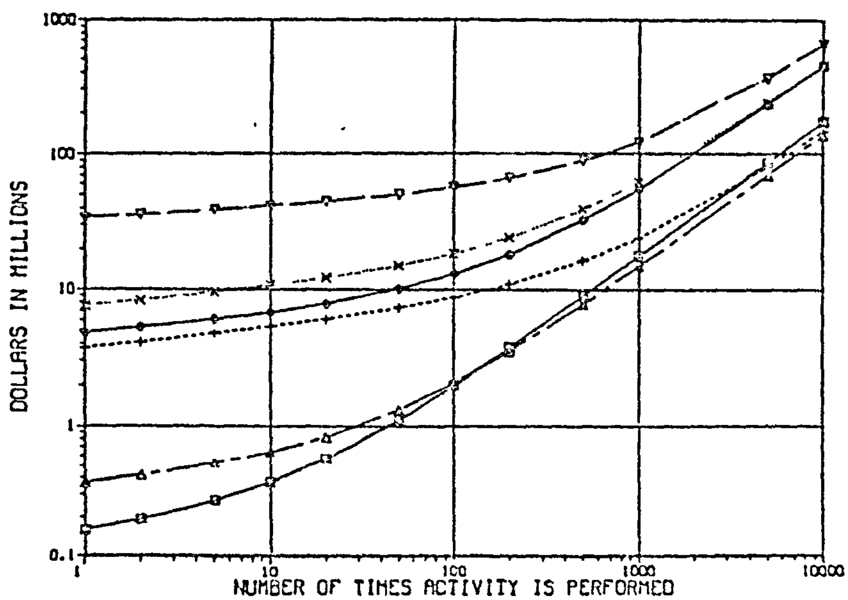


MCDONNELL DOUGLAS

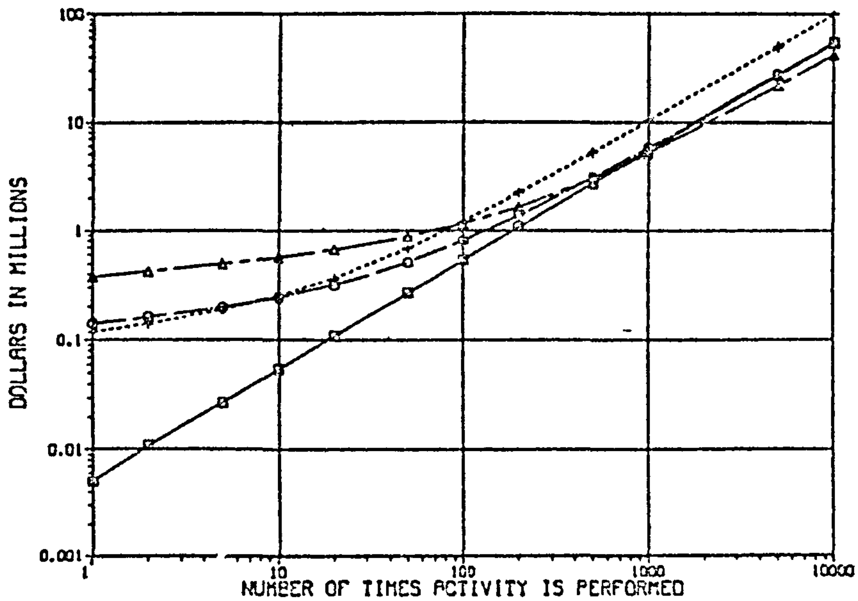
ACT NUMBER 27-PROBLEM SOLVING/DECISION MAKING/DATA ANALYSIS
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



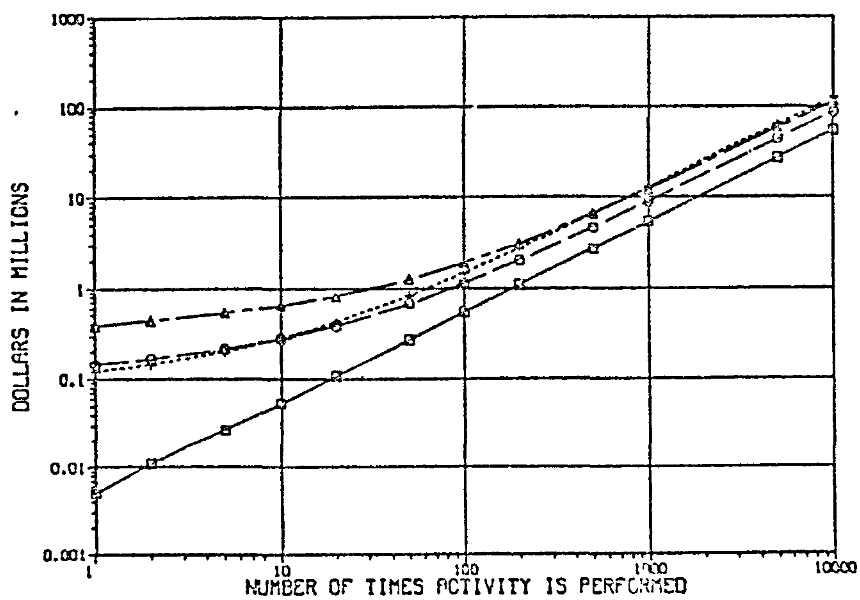
ACT NUMBER 27-PROBLEM SOLVING/DECISION MAKING/DATA ANALYSIS
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS



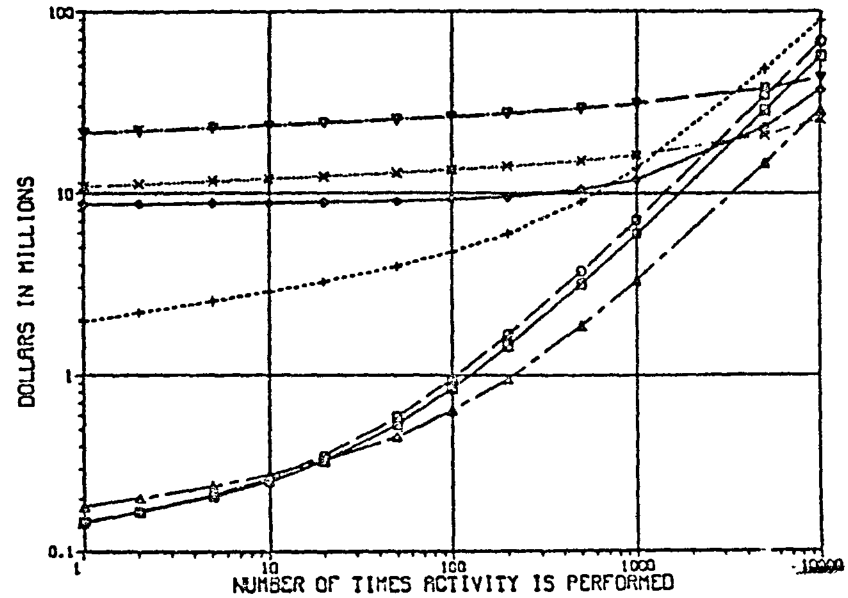
ACTIVITY NUMBER 28-PURSUIT TRACKING
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



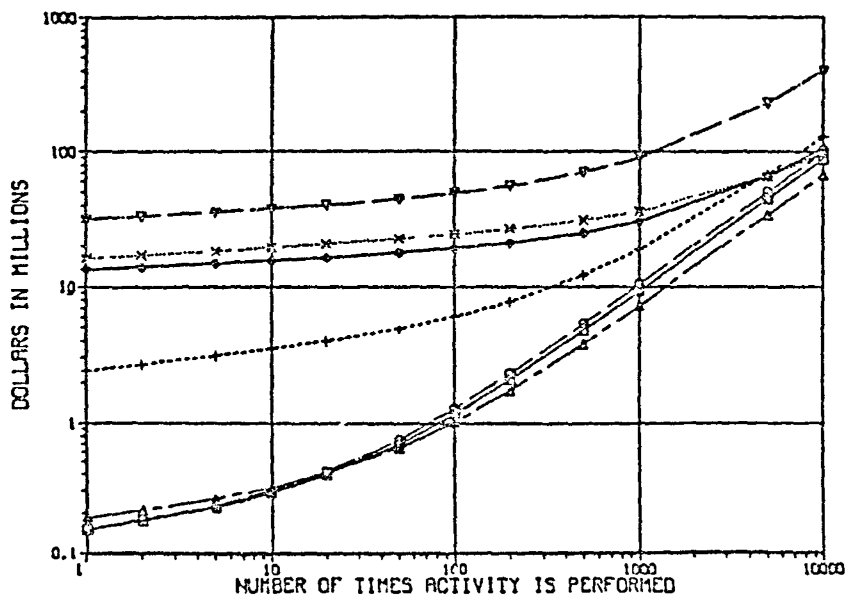
ACTIVITY NUMBER 28-PURSUIT TRACKING
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS



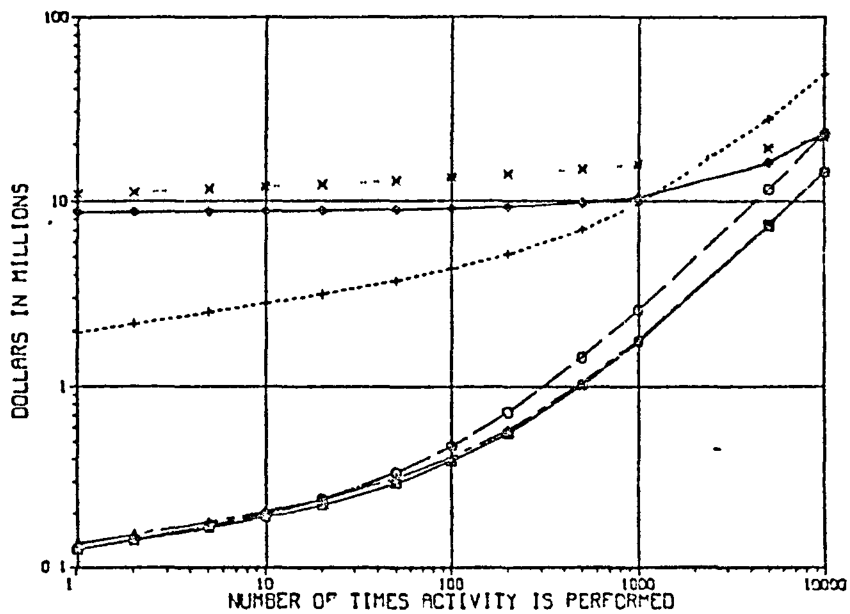
ACTIVITY NUMBER 29-RELEASE/SECURE MECHANICAL INTERFACE
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



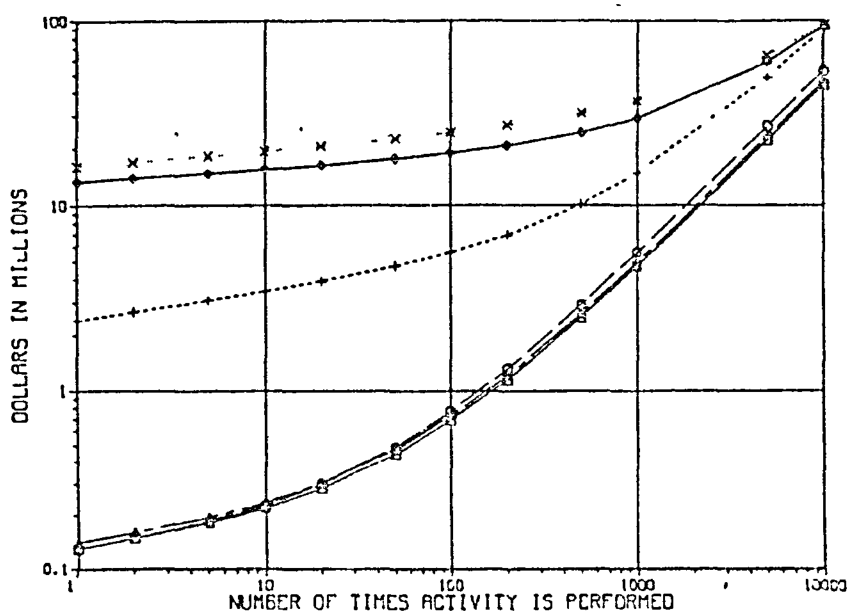
ACTIVITY NUMBER 29-RELEASE/SECURE MECHANICAL INTERFACE
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS



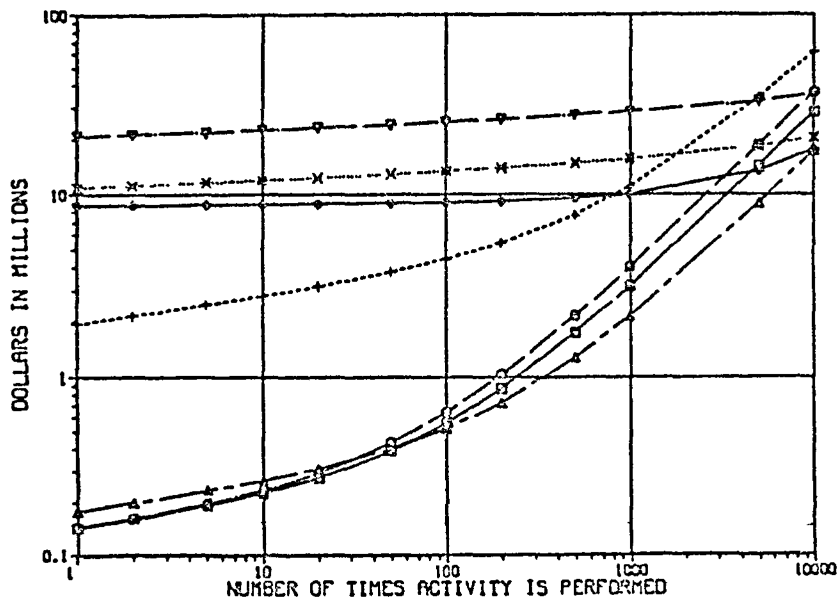
ACTIVITY NUMBER 30-REMOVE MODULE
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



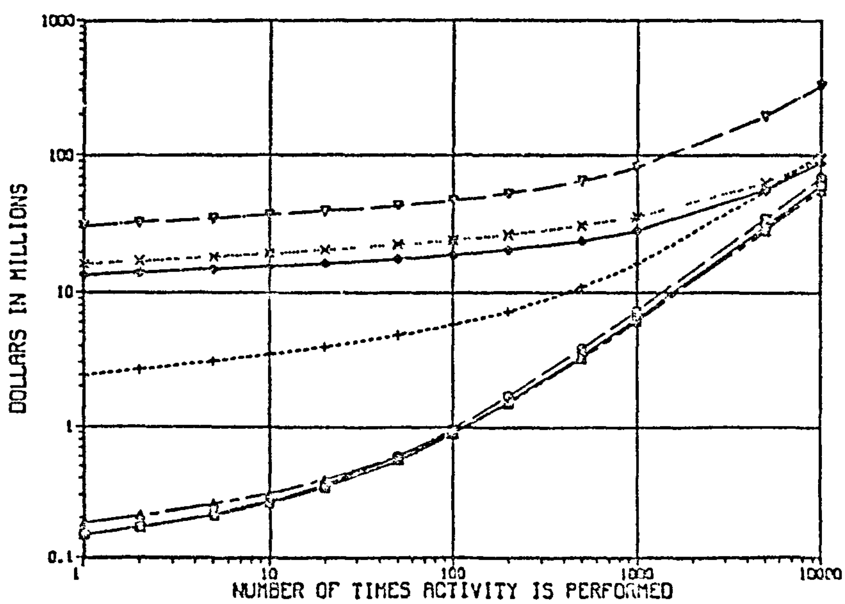
ACTIVITY NUMBER 30-REMOVE MODULE
CUMULATIVE COST VS FREQUENCY
INCLUDING OPERATIONS



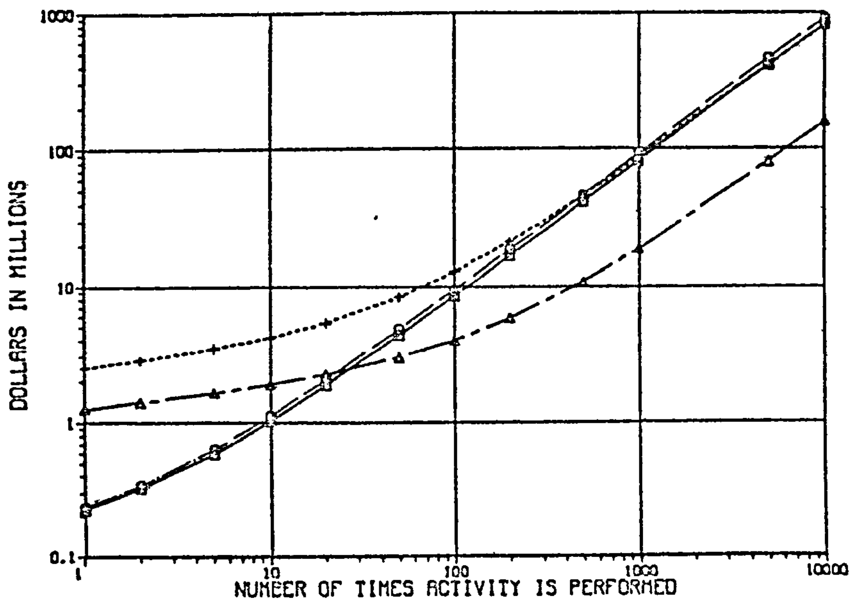
ACTIVITY NUMBER 31-REMOVE/REPLACE COVERING
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



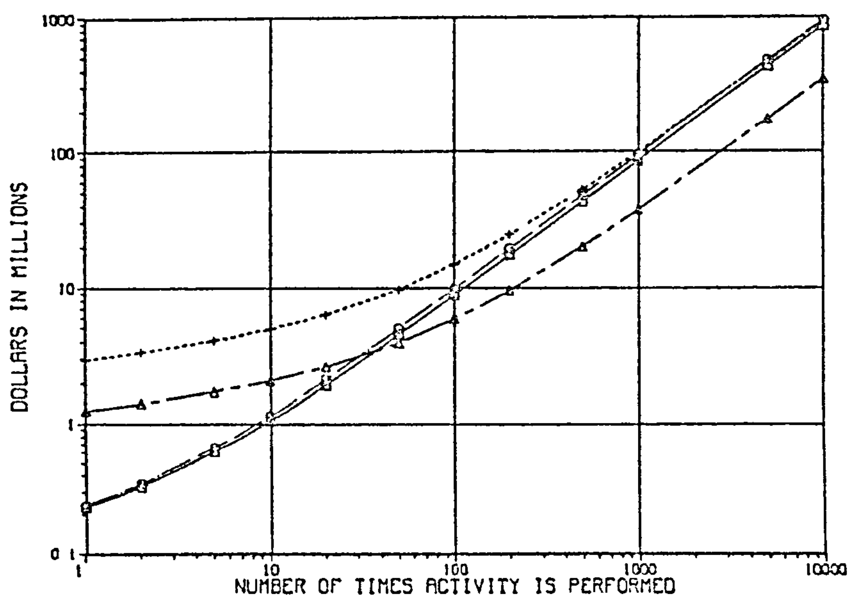
ACTIVITY NUMBER 31-REMOVE/REPLACE COVERING
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS



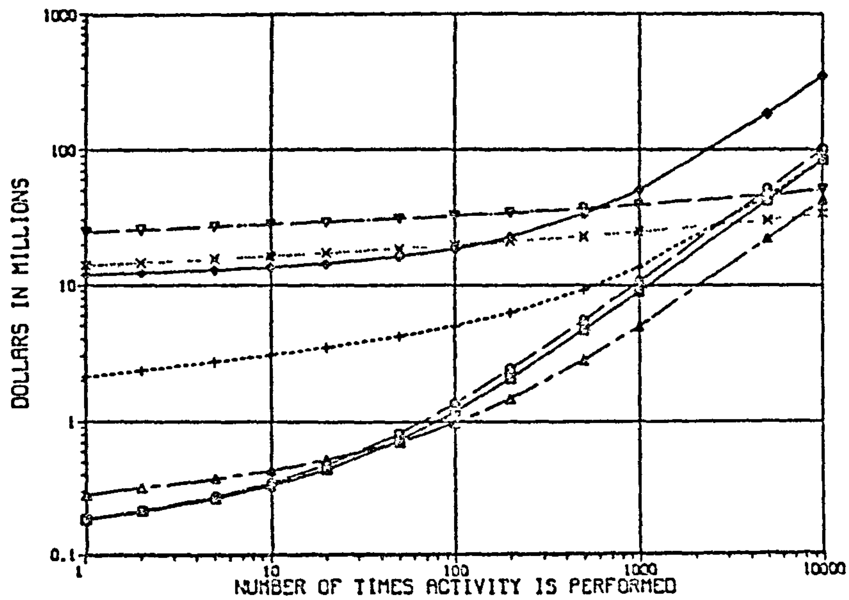
ACTIVITY NUMBER 32-REPLACE/CLEAN SURFACE COATINGS
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



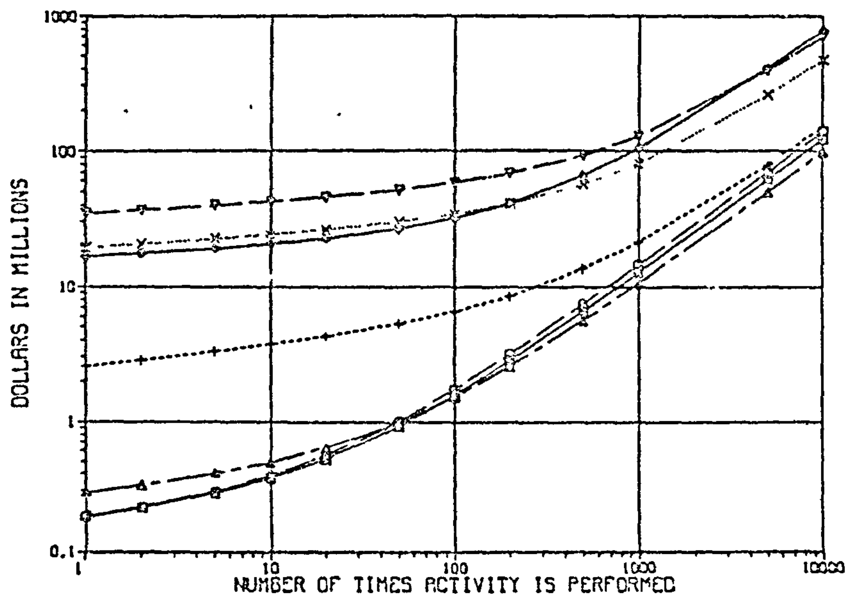
ACTIVITY NUMBER 32-REPLACE/CLEAN SURFACE COATINGS
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS



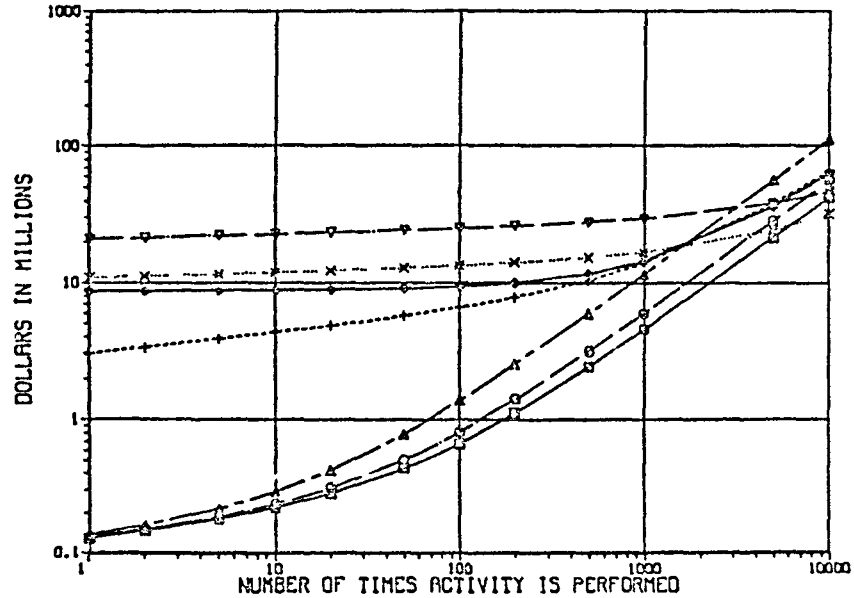
ACTIVITY NUMBER 33-REPLENISH MATERIALS
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



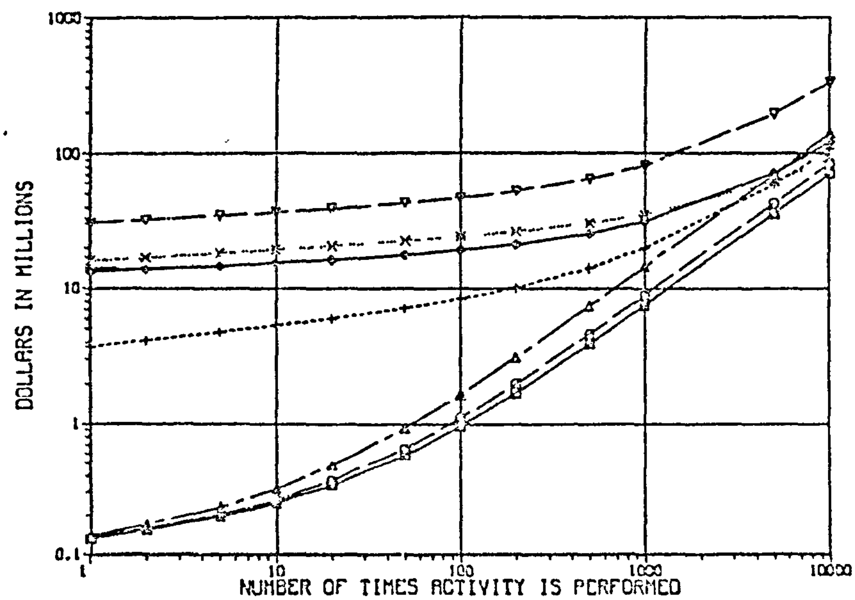
ACTIVITY NUMBER 33-REPLENISH MATERIALS
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS



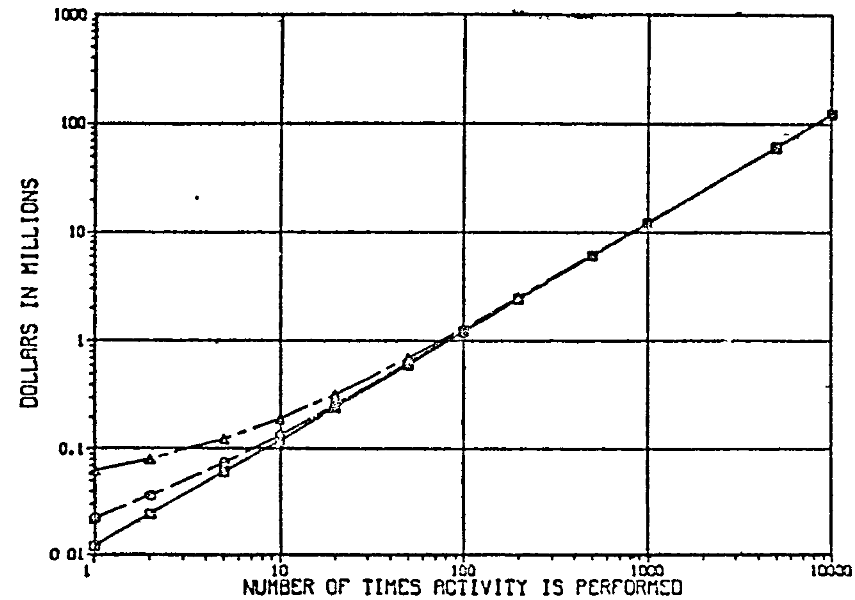
ACTIVITY NUMBER 34-STORE/RECORD ELEMENT
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



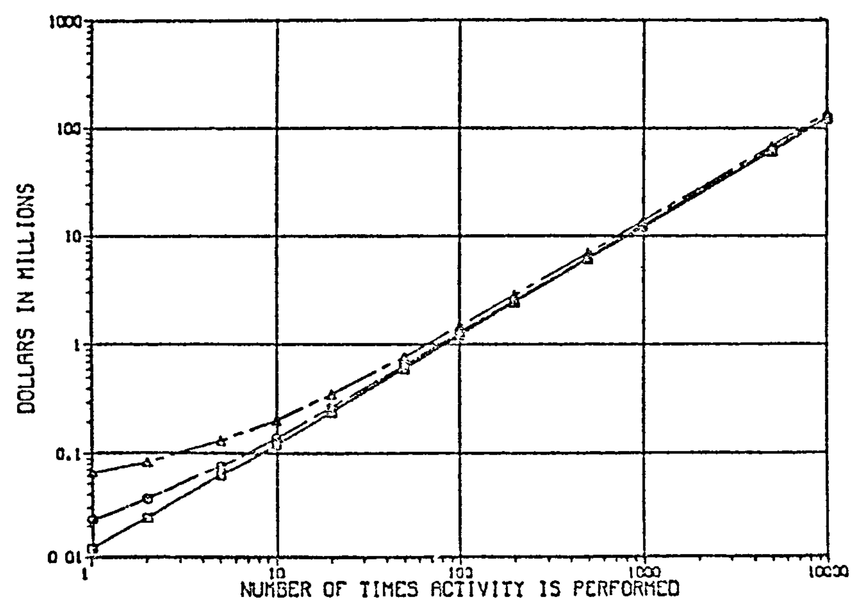
ACTIVITY NUMBER 34-STORE/RECORD ELEMENT
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS



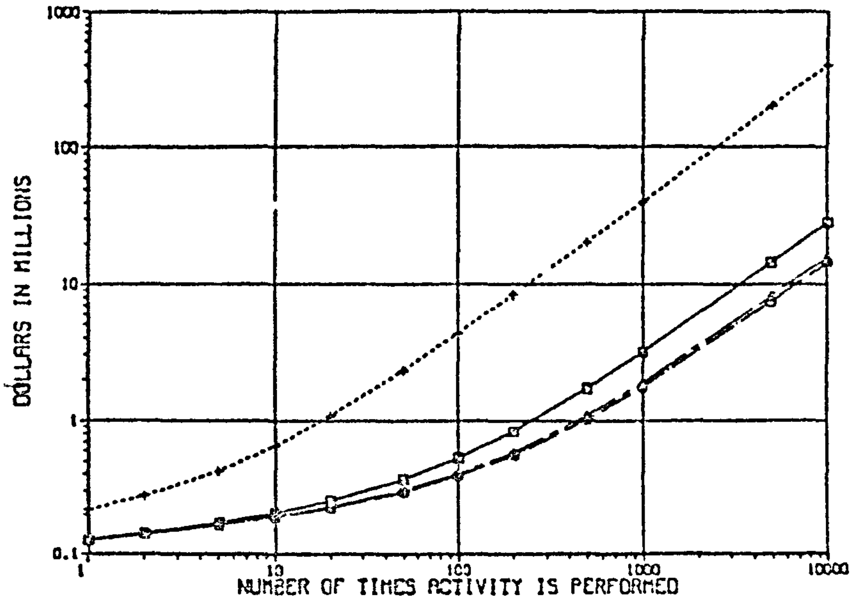
ACTIVITY NUMBER 35-SURGICAL MANIPULATIONS
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



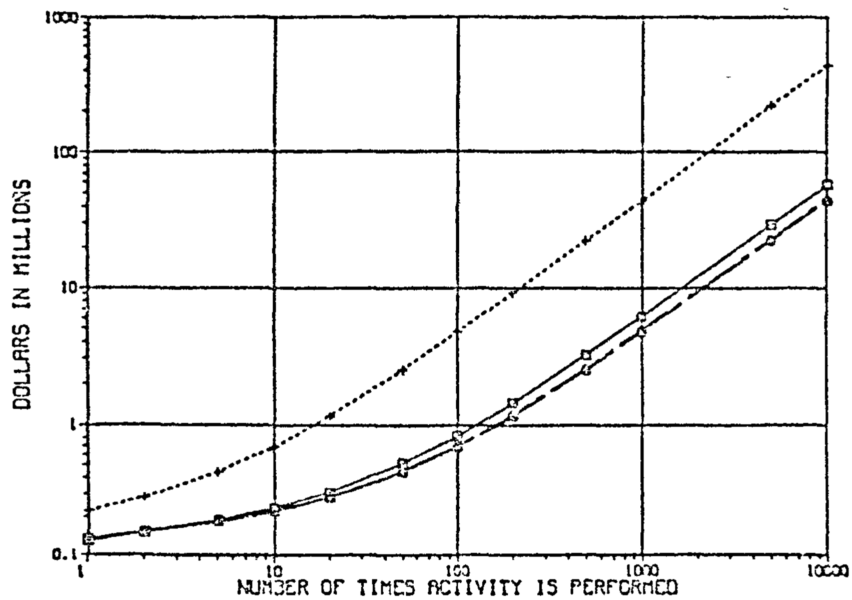
ACTIVITY NUMBER 35-SURGICAL MANIPULATIONS
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS



ACTIVITY NUMBER 38-TRANSPORT LOADED
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS

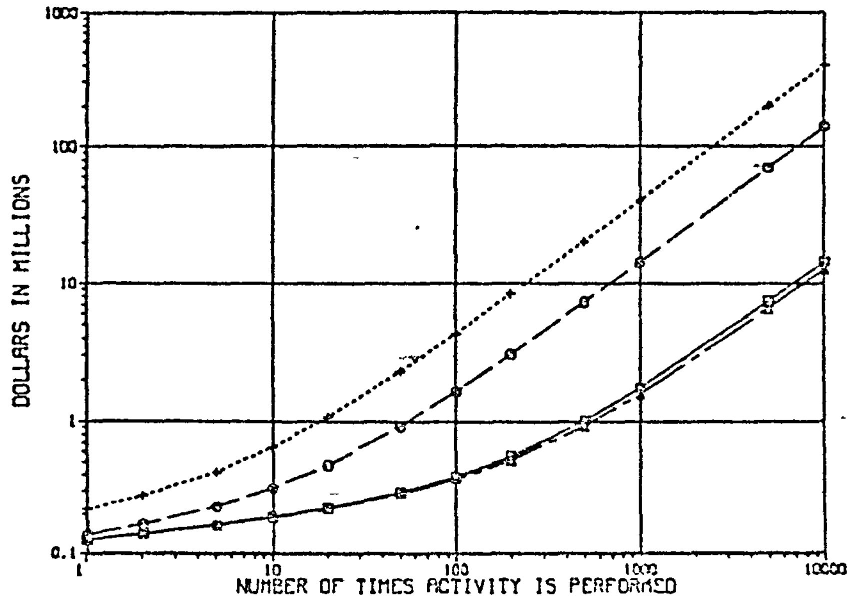


ACTIVITY NUMBER 38-TRANSPORT LOADED
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS

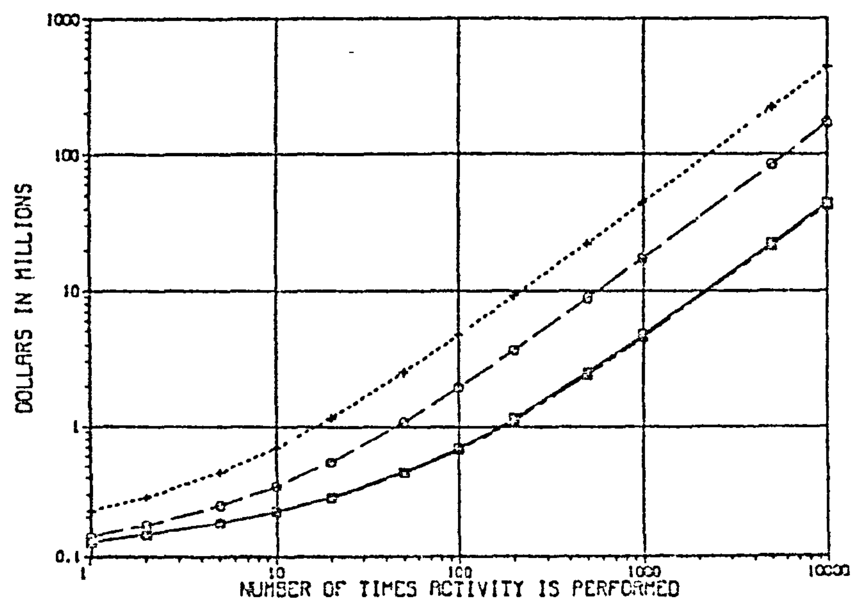


Transport Loaded operations beyond the normal working environment (e.g., to geosynchronous orbit) could require many hours. In the foreseeable future such activities would be performed only in the Supervised or Independent modes. In the THURIS study, costing analyses for transport operations beyond the normal working environment were not performed

ACTIVITY NUMBER 37-TRANSPORT UNLOADED
CUMULATIVE COST VS. FREQUENCY
EXCLUDING OPERATIONS



ACTIVITY NUMBER 37-TRANSPORT UNLOADED
CUMULATIVE COST VS. FREQUENCY
INCLUDING OPERATIONS



Transport Unloaded operations beyond the normal working environment (e.g., to geosynchronous orbit) could require many hours. In the foreseeable future, such activities would be performed only in the Supervised or Independent modes. In the THURIS study, costing analyses for transport operations beyond the normal working environment were not performed.

END

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